PHYSICS NEWS IN 1985

An American Institute of Physics Special Report

Phillip F. Schewe, Editor

THE AMERICAN INSTITUTE OF PHYSICS

The American Institute of Physics is a not-for-profit membership corporation chartered in New York State in 1931 for the purpose of promoting the advancement and diffusion of the knowledge of physics and its application to human welfare. Leading societies in the field of physics and astronomy are its members. AIP's activities include providing services to its Member Societies in the publishing, fiscal, and educational areas, as well as other services which can best be performed by one operating agency rather than dispersed among the constituent societies.

Member Societies arrange for scientific meetings at which information on the latest advances in physics is exchanged. They also ensure that high standards are maintained in the publication of the results of scientific research. AIP has general responsibility for the publication and distribution of journals. The Institute is expected to stay in the forefront of publishing technology and to ensure that the services it performs for its Member Societies are efficient, reliable, and economical.

The Institute publishes its own scientific journals as well as those of its Member Societies; provides abstracting and indexing services; serves the public by making available to the press and other channels of public information reliable communications on physics and astronomy; carries on extensive manpower activities; encourages and assists in the documentation and study of the history and philosophy of physics; cooperates with local, national, and international organizations devoted to physics and related sciences; and fosters the relations of physics to other sciences and to the arts and industry.

The scientists represented by the Institute through its Member Societies number more than 60 000. In addition, approximately 7000 students in over 500 colleges and universities are members of the Institute's Society of Physics Students, which includes the honor society Sigma Pi Sigma. Industry is represented through some 115 Corporate Associate members.

The purpose of the AIP's Public Information Division is to promote a public understanding of the role of physics in society and to provide an appreciation of the developments in physics by assisting Member Societies in conveying information about research, education, and manpower.

Preface

Physics News in 1985, prepared by the Public Information Division of the American Institute of Physics (AIP), is the 17th 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 1985* were selected and prepared by the AIP Member Societies. The following individuals helped to organize the chapters and in some cases to write articles:

The American Physical Society:
Division of Biological Physics—Peter Debrunner, University of Illinois
Division of Chemical Physics—William A. Lester, University of California, Berkeley
Division of Condensed Matter Physics—M. Brian Maple, University of California, San Diego
Division of Electron and Atomic Physics—David E. Golden, North Texas State University
Division of Particles and Fields—James W. Cronin, University of Chicago
Division of Fluid Dynamics—Harry L. Swinney, University of Texas
Division of Nuclear Physics—Harold C. Britt, Los Alamos Scientific Laboratory
Division of Plasma Physics—Harry Dreicer, Los Alamos Scientific Laboratory
Division of High Polymer Physics—H. D. Keith, AT&T Bell Labs.

Optical Society of America:
Jarus W. Quinn, OSA

American Association of Physics Teachers:
Jack M. Wilson, University of Maryland

American Crystallographic Association:
William L. Duax, Medical Foundation of Buffalo

American Astronomical Society:
Harry L. Shipman, University of Delaware

American Association of Physicists in Medicine:
Gary T. Barnes, University of Alabama, Birmingham

American Vacuum Society:
Jack H. Singleton, Westinghouse

AIP Corporate Associates:
Edward C. McIrvine, Xerox

1 November 1985 *Phillip F. Schewe*

Cover:
Electron diffraction pattern of a grain of aluminum–manganese alloy. The pentagonal pattern of sharp diffraction peaks—a pattern never seen before—indicates that the alloy possesses an icosahedral rotation symmetry, long thought to be impossible in solids. This strange new material, made at the National Bureau of Standards by a group led by D. S. Shechtman, is thought to be neither a crystal, in which atoms sit in a periodic gridwork of rows, nor a glass, in which atoms are stuck together in an amorphous tangle. (See the article on "Quasicrystals" in the Condensed Matter Physics chapter.)

Pub. R-225.16, November 1985

Physics News in 1985: An AIP Special Report

ACOUSTICS

Acoustic Chaos

Chaos is a term scientists have adapted from common language to describe the motion or behavior of a system (physical, chemical, and biological) which, although governed by an underlying deterministic law, is irregular and unpredictable. Such systems, often called deterministically chaotic, are nonlinear in nature. Nonlinearity, however, is a necessary but not a sufficient condition for chaos. Another ingredient is the finite precision with which the initial conditions (values of all variables at a given time which determine the system completely) can be known. The slightest variations in the initial conditions may lead to a totally different development of the system at later times.

This sensitive dependence on initial conditions makes deterministically chaotic systems extremely difficult to analyze. It is equally difficult to show unambiguously that a given system belongs to the class of deterministically chaotic systems. Means are needed to distinguish between chaos (deterministically produced irregularity) and noise (statistical irregularity, such as thermal agitation), for which no simple deterministic law can be given. One of these means makes use of the way the irregularity is approached when a parameter of the system is altered.

If a system becomes periodic through the phenomenon of "period doubling," then there is a strong indication that the irregularity attained in this way is of simple deterministic origin. In this route to chaos, the period (the time it takes the

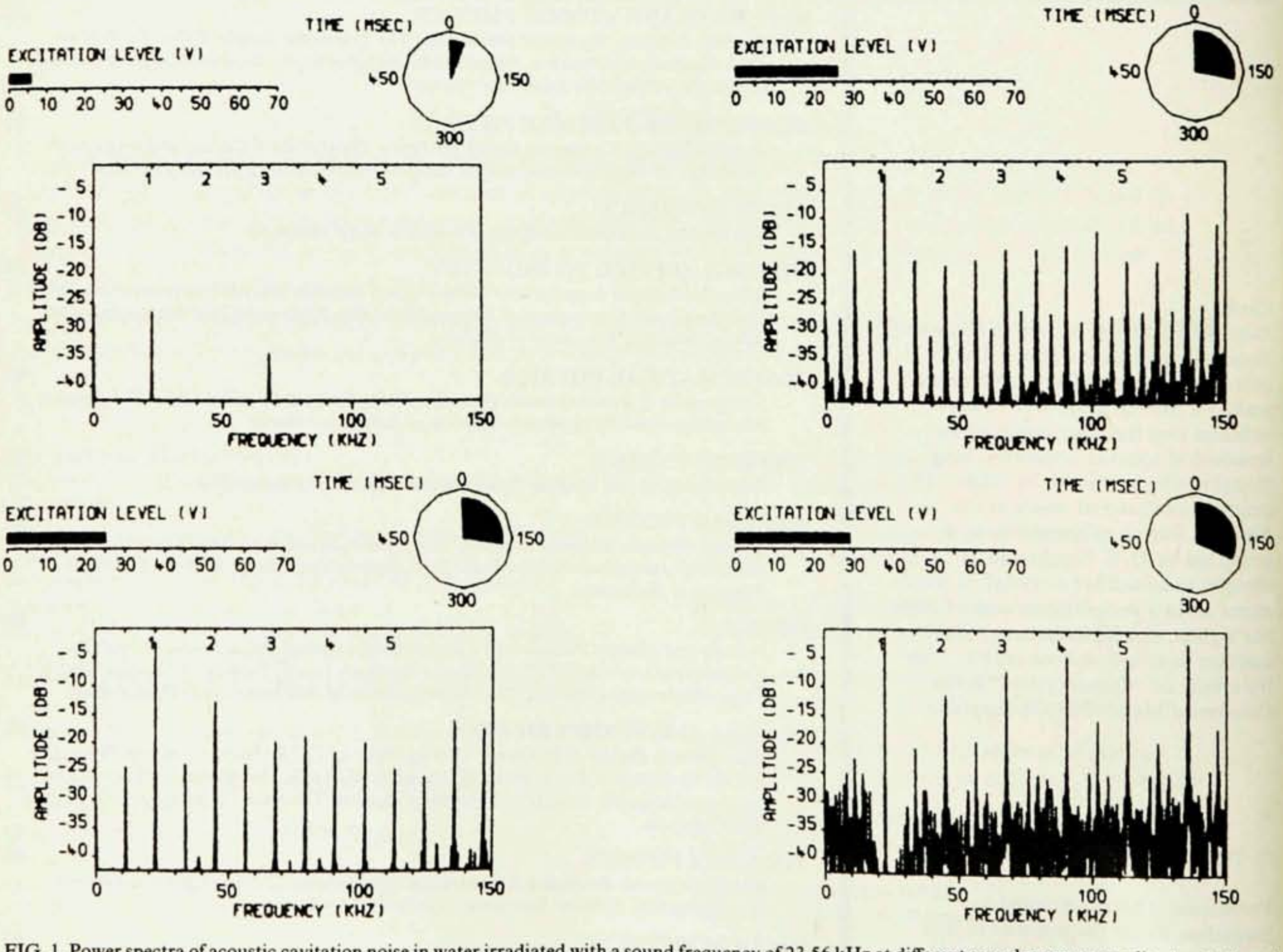

FIG. 1. Power spectra of acoustic cavitation noise in water irradiated with a sound frequency of 23.56 kHz at different sound pressure amplitudes (indicated by the bar below "excitation level" in each plot). The sequence shows the successive "filling" of the spectra by the appearence of spectral lines exactly in the middle between the odd ones.

system to repeat itself) of a system undergoing regular motion doubles when a certain parameter value is reached. The probability is then high that the same mechanism which led to the first period doubling will again produce a further period doubling when the parameter is increased further, and so on, *ad infinitum*. The regular motion that repeated after a certain time thus repeats only after a longer and longer time and ultimately becomes irregular; that is, it does not repeat in a finite time. The roots of this idea have been established in 1977 and 1978 by Feigenbaum (U.S.A.), Grossmann and Thomae (Germany), and Coullet and Tresser (France).

One of the first experimental systems to show period doubling was found in acoustics in 1952 at Göttingen.[1] At that time, however, chaos theory was not available and thus only the first period doubling was noticed. In this experiment a liquid, irradiated with high intensity sound, ruptures to form bubbles or cavities (almost empty bubbles). This phenomenon is called acoustic cavitation and is accompanied by intense noise emission, the acoustic cavitation noise, which, when picked up with a microphone, can be shown to have just the abovementioned properties, namely that when the sound intensity (of a pure tone) is increased from low values there first occurs a period doubling of the period of the sound oscillation in the liquid, then a second period doubling, and so forth. The broadband noise (irregular sound) reached at high input sound intensities (of the pure tone) is thus of deterministic origin: it is acoustic chaos.[2] Figure 1 shows a sequence of power spectra which illustrates the repeated period doubling through successive halving of the lowest frequency until broadband noise appears.

The conversion of a pure tone to broadband noise is caused by the bubbles oscillating in the sound field. Bubbles are nonlinear oscillators, and it can be shown through extensive numerical calculations that they exhibit chaotic oscillations after a sequence of period doublings.[3,4]

The results led to a reexamination of the properties of driven nonlinear oscillators of different kinds as a means of studying their yet unknown chaotic behavior. The aim is to find general laws in the realm of chaotic oscillations. Such laws, when found, will have many applications since oscillatory systems are abundant in nature, ranging from astronomy (the three-body problem or the problem of the stability of the solar system) and other fields of physics (laser oscillations, acoustics, and particle storage rings) to biology (population dynamics, biological clocks, heart beat, and electrical oscillations in the brain). Chaos theory even reaches out for economics and social systems.

Werner Lauterborn, Göttingen University, Federal Republic of Germany

1. R. Esche, Acustica **2**, AB 208 (1952).
2. W. Lauterborn and E. Cramer, Phys. Rev. Lett. **47**, 1445 (1981).
3. W. Lauterborn and E. Suchla, Phys. Rev. Lett. **53**, 2304 (1984).
4. W. Lauterborn, J. Acoust. Soc. Am. **59**, 283 (1976).

ASTROPHYSICS

Astrophysics is the study of physics on the grandest scale, the entire universe. It differs from other fields of physics in that astrophysicists are unable to control or modify the objects under study. For the most part, all of the information we have about the universe is based on measurement of light or other forms of electromagnetic radiation which reach us from celestial bodies. Recent technological advances, combined with our ability to make observations from orbit, have allowed us to probe the electromagnetic spectrum with greater completeness and sensitivity and provided us with glimpses of fundamentally new types of objects. The launch of Space Telescope, expected for August 1986, will provide a dramatic jump in the sensitivity with which we can image the sky in the optical and ultraviolet regions of the electromagnetic spectrum.

But our ability to make observations from space does not by any means make ground-based telescopes obsolete. First, the high cost of space instrumentation means that telescopes in space are considerably smaller than telescopes on the ground, and where the number of photons collected is the limiting factor, telescopes like the Keck 10-m telescope, started this year, will be the most sensitive instruments available. But even more is that the successful interpretation of space observations often requires that the same objects be observed in other parts of the spectrum as well. The identification of photoplanetary disks and the infrared cirrus, reported as one of the highlights of this past year, required data from both the Infrared Astronomy Satellite (IRAS) and optical or radio telescopes.

An additional characteristic of astronomy is that serendipitous, unplanned discoveries also play a leading role. Three of the investigations reported this year are of this nature. For the first time ever, astronomers were lucky enough to spot a supernova in its early explosive stages so that we could study the star as it brightened, not just as it was fading into obscurity. The dusty infrared cirrus which covers the sky at a wavelength of 100 μm was a completely unexpected outcome of the IRAS mission. Perhaps most surprising, but still controversial, was the reported detection of a new type of particle emission from the binary Cygnus X-3. This widely publicized discovery was made by instruments which were originally built to detect proton decay.

Very often, the most publicized events in astronomy involve the detection of fundamentally new types of objects. The discovery of a substellar object, a "brown dwarf" some dozens of times as massive as Jupiter, falls in this category. But very often some fundamental new insights can come from new, more sensitive looks at objects which have been known for some time. The mere existence of the Sun, after all, has been known since ancient times, and even the 5-min oscillations on its surface have been known for 25 years. But, the precise measurements of the power spectrum of these oscillations, first made from the South Pole, have proven to be a very sensitive probe of the solar interior, and launched the science of astroseismology. White dwarf stars, discovered in the 1920's, have turned out to be the stars which we could actually see evolve, as we detect the changing oscillatory period of very hot white dwarfs.

Harry Shipman, University of Delaware

VB 8B, The First Brown Dwarf Outside Our Solar System

With only a single infrared detector operating in the one-dimensional speckle interferometry mode,[1] McCarthy *et al.* were able to use the 4-m telescope at Kitt Peak National Observatory to detect a very cool companion of the nearby M dwarf star Van Biesbroeck 8 (VB8).[2] Their discovery was the first direct detection of a substellar object outside the solar system and the first such body to be seen only by the gradual release of its own gravitational energy. The 1968 discovery of Jupiter's internal energy by Aumann *et al.*[3] showed that such objects exist and subsequent models based on the properties of Jupiter predicted the properties of more massive objects of this type.[4,5]

Because the Arizona based group was able to resolve the brown dwarf companion to VB 8 at two infrared wavelengths, 2.2 and 1.6 μm, and because the distance to the objects was known from other work, the temperature (1360 K), luminosity (3×10^{-5} times that of the sun), and diameter (0.09 that of the sun) were determined. Harrington's astrometric studies of the system have so far been unable to tightly constrain the mass.[6] There is little doubt, however, that it lies in the substellar range between 10 and 50 Jupiters (the least massive stars are thought to be about 80 times Jupiter's mass). Even greater uncertainty surrounds the age of the system; if the age is like that of the solar system, 4 billion years, theory requires a large mass, and VB 8B then lies just below the end of the main sequence where hydrogen burning takes place. If, however, the mass is ultimately established to be much lower, then the system must be quite young and the standard ideas about the ages of late type stars like VB 8 will be altered. In any case the opportunity now exists to resolve these questions through further IR observations, better astrometric measurements and, one hopes, by use of the Hubble Space Telescope.

Jupiter and VB 8B were both formed as parts of more massive stellar systems and hence leave us still searching for individual substellar systems. If John Bahcall's suggestion[7] that such objects may account for the local component of the "dark matter" is correct then these nonplanetary brown dwarfs would be at the same time the most common class as well as the most ubiquitous class of object in the universe. The Infrared Astronomy Satellite (IRAS) surveyed the sky at 12 μm with sufficient sensitivity to detect very cool Jupiter sized objects if they are closer than about 1 pc (3.26 light years), the distance to be expected if Bahcall's suggestion is correct. Preliminary results[8] reported at the Brown Dwarf Conference held at George Mason University in October did not indicate any confirmed objects but did suggest several candidates for study. Because of the very large amount of data processing required it is expected to take several years to fully complete the IRAS search and even then it may require the much greater sensitivity of the next generation of space IR telescopes, either SIRTF (Space Infrared Telescope Facility) or ISO (the European Infrared Space Observatory) to settle the issue of the ubiquity of these cold but fascinating objects.

Frank J. Low, University of Arizona

1. R. Howell, D. McCarthy, and F. Low, Astrophys. J. Lett. **251**, L21 (1981).
2. D. McCarthy, R. Probst, and F. Low, Astrophys. J. Lett. **290**, L9 (1985); Phys. Today **38**, 19 (April 1985).
3. H. Aumann, C. Gillespie, and F. Low, Astrophys. J. Lett. **157**, L69 (1969).
4. J. Tarter, PhD thesis, University of California, Berkeley (1975)
5. D. Stevenson, Proc. Astr. Soc. Australia **3**, 227 (1978).
6. R. Harrington *et al.*, Astrophys. J. **88**, 1038 (1983).
7. J. Bahcall, Astrophys. J. **276**, 169 (1984).
8. F. Low, Proceedings of the Brown Dwarf Conference, George Mason University, 1985.

A Year for Comet Studies

Public interest and excitement has been building during 1985 for the return of Halley's Comet, which will pass closest to the sun on February 9, 1986. At its last return in 1910, Comet Halley became a bright and conspicuous object in the night sky for several weeks, and actually passed between the earth and the sun. This time its return is much less favorable for terrestrial observers, since at its Perihelion on February 9 it will be on the opposite side of the sun from the earth. Nonetheless, U. S. observers should be able to see it during late January and again in April with binoculars, and perhaps with the naked eye from locations far away from city lights and haze. Southerly observers are favored, since at its brightest in late March and early April the comet will be very far south in the sky.

Comet Halley has been recognized as a periodic comet, returning close to the sun about every 76 years, ever since

Edmond Halley in the late seventeenth century showed that the orbits of the comets seen in 1682, 1607, and 1531 were nearly identical. It reappeared, as he predicted, in 1758, and was seen again in 1835 and 1910. Earlier apparitions of the comet have been identified in ancient records, back to at least 240 B.C.

Comets are believed to be some of the most primitive members of the solar system, "dirty snowballs" of ice and rock from the primordial nebula out of which the solar system condensed.[1] They inhabit the far, cold reaches of the solar system, and only if perturbed from their paths out there do some comets swing in near the sun, where the heat causes some of their material to sublime and form an envelope called the coma, as well as (sometimes) a tail. Astronomers can only study these bodies when they are near us and the sun; but since comets hold valuable clues for us concerning the solar system's history and origins, they are of great interest when they do appear.

At the 1986 return astronomers will for the first time use spacecraft to study Comet Halley. Vehicles have been launched by the European Space Agency, Japan, and the USSR, to fly close to the comet and make various types of observations, including pictures. Two U. S. Space Shuttle flights will also study the comet. U. S. astronomers have also made observations from space this year of another comet, known as Giacobini–Zinner. A spacecraft launched in 1978 to study the solar wind was redirected and converted to the International Cometary Explorer (ICE),[2] which passed through Giacobini–Zinner's gaseous tail in September of 1985. The analysis of its observations will be useful to astronomers evaluating the later studies of Comet Halley.

Katherine Bracher, Whitman College

1. J. C. Brandt and R. D. Chapman, *Introduction to Comets* (Cambridge University, Cambridge, 1981).
2. Stephen P. Maran, Sky and Telescope **70**, 198 (Sept. 1985).

Circumstellar, Possibly Protoplanetary Disks

The Infrared Astronomy Satellite (IRAS) mission has done a great deal to focus the interests of astronomers on the processes of star and planet formation. However, as is often true in astronomy, one wavelength region alone cannot provide all the information that is needed. Astronomers, using telescopes on the ground, have observed a disk of dusty material around the bright star Beta Pictoris. The most natural interpretation of this disk is that it is a protoplanetary cloud, either the detritus left over from a recently formed planetary system, or a cloud of dusty material which is about to condense into planets around this hot, young star.

Beta Pictoris is an inconspicuous, fourth-magnitude star in an obscure southerly constellation. It is unlike the thousands of other similarly obscure stars in that it was one of the first four stars to be detected as a source of excess infrared emission by the IRAS satellite.[1] B. A. Smith and R. J. Terrile put a coronograph on the 2.5-m du Pont telescope at Las Campanas Observatory in Chile to block out the light from Beta Pictoris itself, and then used image-processing techniques to produce pictures of the very faint optical features surrounding this star (see Fig. 1). The picture, in the far-red region of the spectrum (at 890 nm), shows a flattened disk, extending northeast and southwest from the star, with an outer radius of 400 astronomical units. (1 AU = 1.5×10^8 km, or the distance from the earth to the sun.) The disk is less than 50 AU thick 300 AU from the star, implying that the disk particles orbit within 5° of the plane of the system. The red light which Smith and Terrile detected is starlight from Beta Pictoris reflected off of the tiny dust grains which make up the disk.

Previous work on other stars produced hints of disks around other stars. Two other IRAS sources, Alpha Piscis Austrinis (Fomalhaut) and Alpha Lyrae (Vega), were surrounded by spherical distributions of emission, but it was not certain that this emission was a flattened disk rather than a spherical shell.[3] Further work[4] indicates that 12 stars show this "Vega phenomenon." A much more distant star, HL Tau, also showed indications of a disk with a radius of 150 AU from ground-based observations, but the greater distance of this star made the disk less obvious from the observations.[3]

For a long time, astronomers have believed that an early step in the evolution of the solar system was the collapse of a

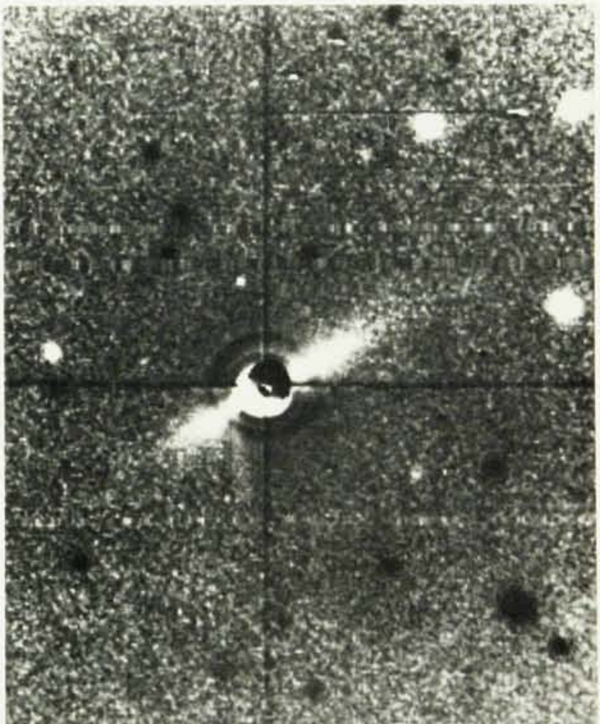

FIG. 1. Circumstellar protoplanetary disk surrounding the star Beta Pictoris. The dark circle at the center is an artifact of the observation process which must screen out the glare of the star in order to reveal the disk material. The bright areas extending away from the star constitute the disk as it appears edge-on.

cloud of dust and gas, called the solar nebula, to form a disk. Planets subsequently formed from that disk, and the flatness of the disk explains why the planets all orbit in the same plane, unlike comets. However, until disks were actually observed around young stars, this scenario was accepted primarily because there seemed to be no other logical way to explain the coplanarity of the solar system. HL Tau is a star currently approaching the main sequence, where stars settle down to fusing hydrogen for billions of years. Beta Pictoris is on the main sequence, but is still a relatively young star, since its high mass (twice the solar mass) dictates that its main sequence lifetime will be relatively short. Future studies of disks like the one around Beta Pictoris will allow us, for the first time, to study the birth of planetary systems directly.

Harry Shipman

1. H. H. Aumann *et al.*, Astrophys. J. Lett. **278**, L23 (1984).
2. B. A. Smith and R. J. Terrile, Science **226**, 1421 (21 December 1984); Physics Today **38**, 19 (February 1985).
3. H. H. Aumann, Bull. AAS **16**, 483 (1984); H. Shipman, *Physics News in 1984*, Phys. Today (January 1985), pp. S-6, S-9.
4. H. H. Aumann, Publ. Astron. Soc. Pacific (October 1985).
5. G. L. Grasdalen *et al.*, Astrophys. J. Lett. **283**, L57 (1984).

Astroseismology

The study of stellar oscillations has been a key element of astronomy and astrophysics since the finding of pulsations in Cepheid variable stars. In the past few years, however, new discoveries have been made that seem destined to convert investigations of stellar pulsations into a tool as powerful for probing the interiors of stars as terrestrial seismology has been for studying the internal structure of the Earth.

The impetus for many of these new developments has come from the rapidly growing interest in solar oscillations.[1] The discovery of the so-called "5-min" oscillations was made 25 years ago, but the great advances in technology in the past several years have permitted the detection of thousands of solar pulsation modes, including long-period oscillations interpreted as "*g* modes" as well as the 5-min "*p*-mode" pulsations. The different modes have appreciable amplitudes in different parts of the solar interior, thus permitting investigations of the spatial variation of various physical quantities within the sun.[1]

One example of great interest is the spatial variation of rotation in the solar interior; a rapidly rotating core would conflict with the interpretation of the observed perihelion precession of Mercury solely in terms of Einstein's general relativistic theory of gravitation. Current measurements yield contradictory results, but they have clearly established that determinations of the internal rotation of the sun from helioseismological data will soon be possible.[2,3] To develop the comprehensive data set needed to resolve the spectrum of solar oscillations and to study its secular behavior, the Global Oscillation Network Group (GONG) has recently proposed the construction of a world-wide network of six identical instruments.[4] Each is designed to obtain spatially resolved Doppler shifts with 8 arc-second resolution at a rate of one complete image per minute. Two candidate instruments, a magneto-optic resonance filter and a Michelson interferometer are currently undergoing tests, and site testing for the network has begun.

Within the past few years, low amplitude, global oscillations resembling those now being actively studied in the sun have also been found in several nearby stars. Five-minute oscillations have now been detected in the Ap star HR 1217 and in Alpha Centauri A, while 10-min oscillations have been discovered in Epsilon Eridani. If these are *p*-mode oscillations like the 5-min oscillations of the sun, the frequency spacing of the modes is expected to scale as the inverse 3/2 power of the stellar radius. Application to HR 1217 suggests that this star has twice the radius of the sun, a typical value for an A star. Similarly, the frequency of Epsilon Eridani seems to scale quite well for this star. Alpha Centauri A, however, does not appear to fit this pattern, suggesting either that the observations have been misinterpreted or that the internal structure of this star is significantly different from that of the sun.[5] Although the "solar-stellar connection" represented by such observations is in its infancy, it holds promise for future investigations of the internal structures of the stars.

H. M. Van Horn, University of Rochester

1. F. L. Deubner and D. Gough, Annu. Rev. Astron. Ap. **22**, 593 (1984); John W. Leibacher *et al.*, Sci. American **253**, 48 (September 1985).
2. H. A. Hill, R. J. Bos, and P. R. Goode, Phys. Rev. Lett. **49**, 1794 (1982).
3. "A Proposal to Study the Solar Interior by Measuring Global Oscillations with a World-Wide Network of Instruments," prepared by the Global Oscillation Network Group (National Solar Observatory, 30 September 1984).
4. T. L. Duvall and J. W. Harvey, Nature **302**, 24 (1983).
5. D. Gough, Nature **314**, 14 (1985).

Supernova Observed in Its Brightening Stage

The colossal stellar explosions called supernovae have been known for decades, but they occur so infrequently in any galaxy that much of their nature is still poorly understood. In particular, we know very little about the types of stars that undergo such destruction, and cannot predict their occurrence so as to watch them as they develop. Usually a supernova is only discovered after it has reached its greatest brightness, some 100,000,000 times more luminous than the sun.

In 1985 astronomers V. S. Niemela, Maria Theresa Ruiz, and Mark M. Phillips reported the first success in catching a supernova in the act of exploding.[1] The supernova, in the galaxy NGC 4699 in the Virgo II cluster, was first spotted by Maria Wischnjewsky on June 6, 1983, at Cerro Calan Observatory in Chile. In four days it brightened by 40 times, and reached its maximum on June 23. At Cerro Tololo Interamerican Observatory in Chile, Niemela, Ruiz, and Phillips photographed the object's spectrum on several nights, from two weeks before maximum light to more than a month after.

The supernova behaved like a typical Type II supernova; these are generally thought to come from massive, rapidly evolving stars, in which a shock wave originates from a collapse of the star's core and travels outward, blasting off the star's outer envelope as it does so. In this case the premaximum spectrum showed strong emissions from hydrogen, ionized helium, and doubly ionized nitrogen, similar to the spectra of the massive stars with extended envelopes called Wolf–Rayet stars. These stars had been previously suggested as possible progenitors for Type II supernovae,[2] but no observational evidence had been presented to show this connection. So perhaps this was a Wolf–Rayet star which exploded.

Niemela *et al.* cautioned, however, that the nitrogen emissions could simply result from the explosion of a massive star, such as a red supergiant with a thick envelope enriched in nitrogen by prior mass loss. They also pointed out that although Type II supernovae are usually found in the spiral arms of galaxies, this one was in the far outer parts of NGC 4699. If it is the product of a massive (and therefore short-lived) star, this suggests that star formation can occur not just in the dense spiral arms of galaxies. In any case, further analysis of the data may add considerably to our knowledge of Type II supernovae and the stars that give rise to such events.

Katherine Bracher

1. V. S. Niemela, M. T. Ruiz, and M. M. Phillips, Astrophys. J. **289**, 52 (1985).
2. A. Maeder and J. Lequeux, Astron. Astrophys. **114**, 409 (1982).

New Telescopes for the 1990s

Much of the explosive growth in the field of astronomy has been produced by tremendous increases in our ability to look for fainter and fainter sources of radiation, at an increasing variety of wavelengths. To do this, astronomers need bigger and more sophisticated instruments. Work on two major projects, a very large optical telescope and the Very Long Baseline Array (VLBA), began in 1985.

If we wish to understand cosmic evolution on the grandest scale, we need to look far back into the history of the universe. We can do this by looking at very distant galaxies, since it takes light a long time to get from there to here. By looking outwards into space we look backwards into time. The difficulty is that the very distant galaxies are also very faint, and in order to get useful information from them it is necessary to get spectra as well as photographs. Even large telescopes like the Mt. Palomar 200-in. are starved for photons.

Until recently, limitations on telescope technology made it impossible to build a telescope significantly larger than the Palomar telescope. (The 236-in. telescope in the Soviet Union has faced a number of operational difficulties.) But a number of clever designers have figured out ways to surpass the limitations of the 200-in. technology and—we hope—turn dreams of 10-m class telescopes into real, functioning "new technology telescopes" (NTT's). The W. M. Keck telescope, to be built by the California Institute of Technology and the University of California (UC), will be a 10-m telescope, with four times the collecting area of the 200-in. Its "segmented mirror" design, in which the 10-m mirror is a mosaic of 36 hexagons, each one of which is carefully kept in its proper place by a computer, is based on development work by UC's Jerry Nelson. The telescope will be located at Mauna Kea, in Hawaii. Caltech and UC will share the observing time on the telescope, with the University of Hawaii getting 10%. Most of the funding for construction of the telescope (estimated at $85 million) was provided to Caltech by the W. M. Keck Foundation; UC has agreed to pay the operating cost for an extended period as well as contributing Nelson's design. Construction is scheduled to start in 1986, and the telescope should see first light in 1992.[1]

Other plans for large telescopes are at relatively advanced planning stages. In one such venture, the University of Arizona and Ohio State University are planning an 8-m telescope on top of Mount Graham, an isolated peak northeast of Tucson. The money is not in hand, but there are reasons to hope that the funds will be made available as part of major fund-raising campaigns being run by the two institutions. Here, the revolutionary design work is being done by Arizona's Roger Angel, who is investigating inexpensive ways to cast and figure large telescope mirrors. Completion is anticipated in the 1990's.[2]

Radio astronomers also need big telescopes, but their most serious limitation is angular resolution rather than collecting area. Because of the long wavelength of radio waves, even the largest single radio dish has a resolving power only equivalent to that of the human eye (about 1 arc minute). However, pairs of radio telescopes working together can be used as interferometers, where the combined signal from the two dishes can be used to pinpoint the location of radio emission in a complex source. This technique, used for a long time in radio astronomy, was the basis for the construction of the Very Large Array radio telescope (VLA), built in the 1970's. The VLA discovered long, skinny radio-emitting jets in quasars and active galaxies, which are the most powerful single sources of energy in the universe. In some cases these jets extend millions of light years away from the galactic core which powers them.

But the smallest structures in quasars and active galaxies, as well as tiny, radio-emitting clouds found in star forming regions, have angular sizes of milliarcseconds and remain unresolved even with the VLA. (A dime 2000 km away has an angular size of one milliarcsecond.) However, radio telescopes at opposite ends of continents, and even on different continents, can be used as the two radio telescopes in an interferometer. Since the 1960's, astronomers have been combining signals from existing radio telescopes in Very Long Baseline Interferometry (VLBI). VLBI has discovered, for example, that radio-emitting clouds in quasars are separating at high speeds which seem to exceed the speed of light, and has been able to map structures no larger than the solar system within the depths of the Milky Way Galaxy. (Of course, the matter in quasars does not actually move faster than light, and the effect is an optical illusion similar to searchlights playing on clouds.)

A significant improvement in our ability to use VLBI techniques will be provided by the VLBA, an array of ten precisely constructed antennas, each 25 m in diameter, and spaced optimally within the United States (including one in the Caribbean). After seven years of study, and after being given high priority by the Field Committee, construction of the VLBA started in May 1985. When the VLBA is complete, in the 1990's, it will be possible to study the energy generation process in quasars in detail, by producing pictures with resolution which is a hundred times better than that of any other image-forming telescope at any wavelength. Interstellar masers, found in star-forming clouds and in the atmospheres of very old stars, can be mapped precisely. Since one can use interferometry to measure the separations of the antennas in the VLBA, it will also be very useful for geophysical studies.[3]

Some years ago, the Astronomy Survey Committee of the National Academy of Sciences, called the Field Committee, recommended a number of major projects for astronomy.[4] Some of these dreams are beginning to become real, and other projects are still under active discussion. For example, the National Science Foundation is supporting further technology development for large optical and infrared telescopes, as recommended by the Field report. The top priority major instrument recommended by the Field Committee, the Advanced X-Ray Astrophysics Facility (AXAF), is under active development at NASA.

Harry Shipman

1. M. Mitchell Waldrop, Science **227**, 275 (18 January 1985).
2. M. Mitchell Waldrop, Science **228**, 831 (17 May 1985); D. L. Mammana, Sky and Telescope **70**, 10 (July 1985).
3. K. I. Kellermann and A. R. Thompson, Science **229**, 123 (12 July 1985); M. Gordon, Sky and Telescope **69**, 487 (1985).
4. Astronomy Survey Committee, *Astronomy and Astrophysics for the 1980s* (National Academy Press, Washington, D.C., 1982).

Signals from Cygnus X-3

At the beginning of the year it appeared that a major breakthrough had been achieved in the long quest for the origin of ultrahigh energy cosmic rays.[1] It now appears that several binary x-ray sources may also be sources of photons with energies of 10^{15}–10^{16} eV. These photons might originate from the decay of neutral pions produced by interactions of cosmic rays with matter in the environment of the companion star.[2] The cosmic rays (presumably protons or possibly heavier ionized nuclei) are somehow accelerated by the compact primary partner, and some fraction that do not interact are injected into the galaxy where they become part of the general cosmic ray population. Indeed, the cosmic ray luminosity (10^{39} ergs/sec) required to explain the photon signal from Cygnus X-3 is so large that that source alone could supply all the galactic cosmic rays in the 10^{16}–10^{17} eV energy range at the current epoch.[3]

An interesting feature of Ref. 3 is the suggestion that a monoenergetic cosmic ray beam naturally produces the hard photon energy spectrum that is observed. This occurs because the energetic photons from decay of neutral pions make electromagnetic cascades, either in the ambient magnetic fields or in the dust. The resultant photon spectrum from such cascades has nearly equal amounts of energy in equal logarithmic intervals, as observed. The nature of the acceleration mechanism of the cosmic rays is not certain and is under active investigation.[1,2] The primary cosmic ray spectrum, however, can be quite different from that of the observed secondaries.[3]

During 1985 a series of events occurred that has both intensified interest in Cygnus X-3 and made the nature of its ultrahigh energy signal mysterious and even more intriguing. Two groups with deep underground detectors have reported[4,5] seeing muons with exactly the phase of the 4.8 hr x-ray period from Cygnus X-3, which is known with an accuracy of better than one part in 10^6. This is a truly startling claim because no known particles capable of producing a penetrating signal at a deep detector can travel the 30,000 or more light years from the source while maintaining the phase information.

The particles seen deep underground are almost certainly penetrating muons, which are far too short lived to be themselves the signal carrier. Most muons detected deep underground are produced by cosmic ray protons and nuclei that interact in the Earth's atmosphere. However, these cosmic rays are charged and cannot travel in straight lines through the galactic magnetic field. Neutrons could do the job, but their lifetime at the appropriate energy is too short by some three orders of magnitude. Photons are ruled out because they do not produce enough muons of sufficient energy to penetrate through the rock to the detector.[6]

The only other known candidate for producing the underground signal is the neutrino. The muon type neutrino can interact in matter via its charged-current interaction to produce a muon; however, the probability for this process to occur is very low because the neutrino interacts only weakly. Indeed high energy neutrinos are expected to be produced in many astrophysical processes, including mechanisms like the one described by Eichler and Vestrand to produce photons at Cygnus X-3. Moreover, the advent of neutrino astronomy would be extremely important for astrophysics precisely because the neutrino interaction probability is so small that it can escape from dense environments that are opaque to photons. The flux of neutrinos expected from Cygnus X-3, however, is much smaller than would be required to produce the muon signal of Refs. 4 and 5.[7] More importantly, the angular dependence of the signal is like that of ordinary muons of atmospheric origin. Most of the signal comes when the thickness of rock between the source and the detector is a minimum. On the contrary, because of its small interaction probability, the neutrino ought to give a signal regardless of the overburden along the line of sight to the source. There should even be upward-going neutrino-induced muons. Thus, whatever these experiments may portend, it does not appear to be the beginning of neutrino astronomy.

All the suggestions that have been attempted to explain an underground signal from Cygnus X-3 in terms of new particles—whether they are weakly interacting photinos, strongly interacting hadrons, or strange quark matter—suffer serious difficulties and inconsistencies. In general, when normalized to the underground flux, strongly interacting objects tend to produce too many surface showers and weakly interacting particles tend to require too much power at the source.

A very puzzling feature of the data itself is its angular distribution. In the case of the NUSEX experiment (a detector located under Mont Blanc in Europe) the signal is spread over a region about Cygnus X-3 that is several times the angular resolution of the detector.[4] In the Soudan I experiment (located in a mine in Minnesota) the direction that maximizes the signal seems to be somewhat different from the true direction to the source.[5] In addition, evaluating the statistical significance of a time-varying signal from a point source in the presence of a nonrandom background is complex and the subject of much debate and criticism.

Because of these difficulties, confirmation of the underground results by other groups is crucial. Not surprisingly, in view of the potential importance such an effect would have, all the groups with underground detectors are looking, including many designed to search for proton decays (such as the IBM detector in Ohio and the HPW detector in Utah). One group reported an upper limit nearly one order of magnitude below the result of Soudan I, but not in conflict with the deeper NUSEX data. Another detector (Frejus), much larger than NUSEX at a similar location, has a particularly important role to play in clarifying the status of the signal deep underground. As of August 1985, it had statistics comparable to NUSEX; in two years running time this will be quadrupled.

Regardless of the outcome of the underground situation, probably the most important task for high energy cosmic ray physics at present is to clarify the nature of the signals from Cygnus X-3 and other x-ray binaries seen with surface detectors.[8] The sources are highly variable, and current results are sometimes conflicting and of marginal statistical significance. Order-of-magnitude improvements in the air shower experiments would likely establish firmly the existence of the signals. Properly instrumented surface arrays could establish the electromagnetic origin of the signal by looking for characteristically muon-poor showers. In combination with the atmospheric Cherenkov measurements, which explore the TeV range, one could then study natural accelerators at work up to 10^5 TeV.

T. K. Gaisser, Bartol Research Foundation, University of Delaware

1. Kenneth Brecher, in *Physics News in 1984*, Phys. Today (January 1985), p. S12; P. Kevin MacKeown and Trevor C. Weekes, Sci. American **253**, 60 (November 1985).
2. W. Thomas Vestrand and David Eichler, Astrophys. J. **261**, 251 (1982) and Nature (1985) in press.
3. A. M. Hillas, Nature **312**, 50 (1 November 1984).
4. G. Battistoni *et al.*, Physics Lett. B **155**, 465 (6 June 1985).
5. M. L. Marshak *et al.*, Phys. Rev. Lett. **54**, 2079 (13 May 1985).
6. Todor Stanev and Ch. Vankov, Phys. Lett. **158**, 75 (August 1985).
7. T. K. Gaisser and Todor Stanev, Phys. Rev. Lett. **54**, 2265 (20 May 1985).
8. Both surface and underground data and their interpretation were discussed extensively at the XIX International Cosmic Ray Conference at La Jolla last August. Much of this material is contained in the post-conference volume of Rapporteur and Highlight papers.

The Direct Detection of the Slow Pace of Stellar Evolution

The life cycles of stars generally proceed at a slow, stately pace, with time scales which range from 10^6 to 10^{10} years. These slow evolutionary processes are occasionally punctuated by violent events, like supernova explosions, which are easy to observe but difficult to interpret. The recent measurement of a changing pulsational period of a rapidly evolving, dying star represents one of the first direct measurements of long-term, secular stellar evolution.

About six years ago, in one of the first observations made at the multiple mirror telescope observatory at Mt. Hopkins, Arizona, a very hot prewhite dwarf star designated as PG 1159-035 was discovered to be a variable star. (The "PG" designation refers to the Palomar–Green survey[1] in which this star was first identified.) White dwarf stars are dying cinders, with little or no internal sources of nuclear energy, and they are the final evolutionary states of low mass stars like the sun. Cooler white dwarf stars, with surface temperatures near 12,000 K, were known to pulsate, but PG 1159, with a surface temperature exceed 100,000 K, was an example of a new class of variable star. The evolutionary time scales of stars like this are relatively rapid, of order 10^6 years or less, suggesting that a direct measurement of the effects of cooling on the pulsation period might be possible.

By the 1984 observing season, a sufficient amount of data had accumulated so that expectations that the evolution of PG 1159-035 could be detected observationally were realized. Winget and collaborators measured a period decrease in this object, with a time scale of 1.4×10^6 years.[2] A total of 4.4 years of data, obtained mostly at the McDonald Observatory in Texas and partially at the South African Astronomical Observatory, were used in the analysis. While the temperature and thus the evolutionary time scale of PG 1159 is rather uncertain, the time scale of roughly a million years is in line with theoretical expectations.

An initial difficulty, however, was that the theoretical calculations, done more or less in parallel with the final interpretation of the data, indicated that the period should increase in contrast to the period decrease which was observed.[3] The difficulty is that hot white drawfs like PG 1159 are both cooling and contracting, and the effects compete in that cooling tends to increase the period and contraction tends to decrease the period.[4] While it is possible that refinements to the models may change the current assessment that cooling is more important than contraction, another way to reconcile theory and observation may be to include the effects of rotation and assume that the star is rotating with a period of one to a few hours.[5] Such a rotation period is entirely reasonable for a white dwarf star, and is consistent with other measurements of, or upper limits to, the rotation of these objects.

There are a number of applications of this idea which go beyond the simple measurement of the period change in one star. There are three other hot white dwarf variable stars similar to PG 1159-035, but discovered more recently; period changes in these objects might possibly be detected in a few years, since one's ability to measure a period change increases rapidly as the available data cover a long time base. Another recently discovered class of cooler white dwarf variables, which have He-rich photospheres and temperatures near 26,000 K, still cool fast enough so that a few years of observations can detect a period change. Because these stars are not contracting, the effects of cooling and contraction will not be confused. There are still sufficiently few of these variable stars so that the discovery of additional objects, and better determinations of the temperatures of the ones that we know of, offer a number of opportunities for future research.

Harry Shipman

1. R. F. Green, M. Schmidt, and J. Liebert, Astrophys. J. Suppl. (in press).
2. D. E. Winget, S. O. Kepler, E. L. Robinson, R. E. Nather, and D. O'Donoghue, Astrophys. J. **292**, 606 (1985).
3. S. D. Kawaler, C. J. Hansen, and D. E. Winget, Astrophys. J. **295**, 547 (1985).
4. D. E. Winget, C. J. Hansen, and H. M. Van Horn, Nature **303**, 781 (1983).
5. S. D. Kawaler, D. E. Winget, and C. J. Hansen, Astrophys. J. (to be published); S. D. Kawaler, D. E. Winget, I. Iben, and C. J. Hansen, *ibid.* (to be published).

BIOLOGICAL PHYSICS

Contact X-Ray Microscopy

Developed at the IBM T. J. Watson Research Center, contact x-ray microscopy is an elegant technique for producing unique high-resolution images on x-ray-sensitive material. It uses a variety of x-ray sources and takes advantage of the high magnification of an electron microscope. In particular, with a flash x-ray source providing pulse durations measured in nanoseconds, researchers have for the first time observed the inner structure of a live human cell.

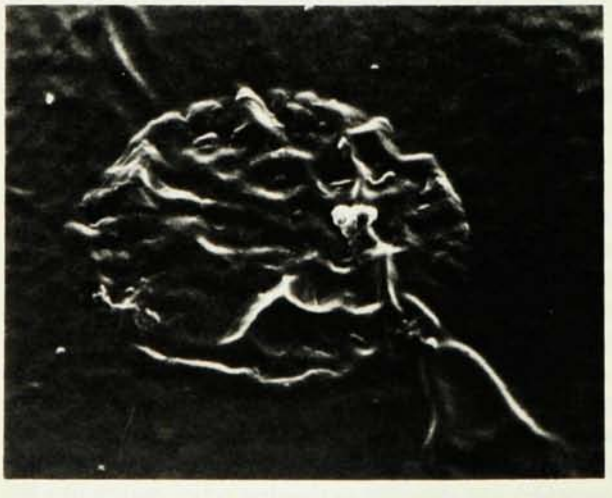

FIG. 1. The first x-ray image of a live, human blood platelet. Made with the new technique of contact x-ray microscopy using a flash x-ray source, the image shows details in the structure of the platelet that have never before been seen.

X-ray images were first obtained on photographic emulsions in the early 1900's and were viewed in an optical microscope. Since then, x-ray imaging has been used extensively for medical and industrial purposes as well as for scientific research. But progress towards a high-resolution x-ray-imaging process was hampered by the lack of appropriate technology.

With the introduction of the commercial electron microscope in the late 1940's, a new world opened up for biology and solid-state physics. However, the specimens for the electron microscope required special processing, staining, and sectioning, so biological samples were never alive when viewed. Contact x-ray microscopy, which overcomes that problem, is an outgrowth of x-ray lithography, a technique being developed for fabricating integrated circuits.

Contact x-ray microscopy images are made by first placing the specimen in intimate contact with a thin film of x-ray-photosensitive polymeric material called a resist. The specimen can be mounted directly on the resist, on an x-ray transparent substrate, or on an electron-microscope grid. After exposure, the resist is developed and exhibits a three-dimensional relief structure that is actually a photon-density map of the specimen, in which the height of the remaining resist is proportional to the x-ray absorption in the specimen. The resist is then coated with a metal layer, only 10 nm thick, which acts as a conductor to prevent charging. The resist is then ready for examination in a scanning elctron microscope or a transmission electron microscope. The electron microscope magnifies the resist profiles at high resolution.

Researchers in this area have employed a variety of x-ray sources to solve a variety of problems. These sources range from the standard laboratory x-ray unit to a source tunable to any desired wavelength, to a source that produces very short pulses of x rays.

The standard laboratory x-ray source produces x rays by electron bombardment against a solid target. The wavelength of the x-ray emission from such a source depends upon the target material, so changing targets provides a way of making a number of discrete x-ray wavelengths available.

A synchrotron is the most intense continuous source available for soft x rays. As an x-ray source, it is made tunable with a grating monochromator. Tunability allows the user to obtain images of a variety of specimens both above and below the absorption edges of all the elements they contain. For a particular element, the difference between images taken just above and just below its absorption edge will indicate the location of that element as well as its concentration.

The accompanying figure (Fig. 1) is an x-ray contact image of a living blood platelet that was imaged while it was in a wet chamber surrounded by a nutrient. It shows arms, called pseudopods, extending from the interior of the platelet. Also seen is a formation of small spherical particles at the base of the pseudopod. These particles had never before been seen.

X-ray contact imaging technology has progressed far enough for the results to be of interest to research biologists. Not only is there a dramatic difference between images dependent on electron and photon absorption—there is also a significant difference between x-ray images taken at different wavelengths.

Ralph Feder, IBM T. J. Watson Research Center

1. R. Feder, V. Banton, D. Sayre, J. Costa, M. Baldini, and B. Kim, Science **227**, 63 (4 January 1985).

CHEMICAL PHYSICS

Vibration–Rotation Laser Spectroscopy of Negative Ions

In the last decade there have been significant milestones in the field of high resolution infrared spectroscopy of molecular ions, primarily owing to the development of widely tunable, infrared laser sources and innovative methods for enhancing ion absorption sensitivity. The first high resolution observation of a molecular ion in the IR was in 1976 by W. H. Wing and co-workers, who utilized an ingenious method of Doppler tuning beams of HD^+ and HeH^+ ions into resonance with a CO laser by accelerating potentials.[1] An IR spectrum of H_3^+, the first polyatomic molecular ion observed, was obtained by T. Oka in 1980,[2] who monitored the direct absorption of a tunable difference frequency laser through a 32-m long, cooled H_2 discharge. With the introduction of velocity modulated discharge absorption techniques by R. J. Saykally and co-workers,[3] there has been a considerable surge of polyatomic positive ion IR spectra reported in the literature by several laboratories.

Corresponding progress in the arena of high resolution vibration-rotation spectra of negative ions has proven more elusive. This is largely due to the difficulty in obtaining adequate concentrations of negative ions in these electrical discharges for direct absorption methods to be feasible. For negative molecular ions with sufficiently low detachment thresholds, vibrationally and rotationally excited levels can decay or autodetach to the corresponding neutral species plus an electron. For this class of negative ions, tunable infrared laser photoelectron spectroscopy can provide both the requisite sensitivity and resolution. In order for this approach to succeed, detachment lifetimes must be sufficiently long that the autodetachment resonances from internally excited states appear as sharp features on the relatively smoothly varying signal from direct photodetachment.

This technique has recently been successfully demonstrated on NH^- by a team of scientists at the Joint Institute for Laboratory Astrophysics and the Department of Chemistry at the University of Colorado.[4] The molecular constants obtained for NH^- from this data are in excellent agreement with *ab initio* calculations.[5] The technique of high resolution infrared laser photodetachment spectroscopy can be extended to many other species with higher electron affinities by exciting overtones, combination bands, or hot bands of the negative ions.

David Nesbitt, Joint Institute for Laboratory Astrophysics, Boulder, Colorado

1. W. H. Wing, G. A. Ruff, W. E. Lamb, Jr., and J. T. Speyeski, Phys. Rev. Lett. **36**, 1488 (1976).
2. T. Oka, Phys. Rev. Lett. **45**, 531 (1980).
3. C. S. Gudeman, M. H. Begemann, J. Pfaff, and R. J. Saykally, Phys. Rev. Lett. **50**, 727 (1983).

4. D. M. Neumark, K. R. Lykke, T. Anderson, and W. C. Lineberger, J. Chem. Phys. (submitted).
5. P. Rosmus and W. Meyer, J. Chem. Phys. **69**, 2745 (1978).

Reaction Rates and Friction: Classical Activation and Quantum Tunneling

The activated passage of an effective particle over a barrier lies at the heart of many important processes in chemical physics. Examples include chemical reactions, thermal desorption, structural isomerizations in macromolecules, and the decay of metastable states. For many years the leading theory that describes the rates for such processes has been the Transition State Theory. This theory pictures the passage as a free flight over the barrier, with no dynamical influence arising from the solvent, lattice, or "bath" with which the particle is in contact.

The critical role of the surroundings in determining a barrier passage rate was first elucidated in a classic paper[1] by H. A. Kramers, who described a simple one-dimensional Markovian Brownian motion in terms of a friction constant. In recent years there has been a veritable flood of research testing, extending, and superseding the original Kramers theory, and significant advances have been made in connection with the influence of friction on aspects of the rate problem.[2-5]

One example is the effect of memory friction on reaction rates.[2] For a simple barrier passage, the friction constant in Kramers' theory for the diffusive transmission factor is replaced by a frequency-dependent friction,[2] a difference reflecting the fact that the rate is sensitive to the short time scale rather than the long time scale interaction of the reaction system with its surroundings. This effect is apparent in recent experimental isomerization studies.[3]

The multiple dimensions within the reacting system have also come under scrutiny.[4] In particular, internal molecular degrees of freedom can dramatically influence low-friction behavior. The reaction rate becomes determined by collisional energy activation. This phenomenon is revealed as a peak in a plot of the rate as a function of pressure or viscosity.

At lower temperatures, thermally activated "hopping" processes become rarer and the effect of quantum tunneling becomes increasingly important.[6-10] The crossover between thermal activation and quantum tunneling, which occurs at a temperature T_0, is marked by the softening of a fluctuation mode around the saddle point of the potential energy surface.[7] At temperatures lower than T_0, the rate is dominated by quantum tunneling.[8] In particular, a recent theory shows that at very low temperatures, the dissipation leads to a universal exponential T^2 thermal enhancement.[9] This T^2 law should be valid for all systems with finite low-frequency friction. In recent months this characteristic behavior has been observed in experiments on low temperature Josephson junction systems.[10]

Peter Hanggi, Polytechnic Institute of New York

1. H. A. Kramers, Physica (The Hague) **7**, 284 (1940).
2. R. F. Grote and J. T. Hynes, J. Chem. Phys. **73**, 2715 (1980); P. Hanggi and F. Mojtabai, Phys. Rev. A 26, 1168 (1982).
3. S. P. Velsko, D. H. Waldeck, and G. R. Fleming, J. Chem. Phys. **78**, 249 (1983); B. Bagchi and D. Oxtoby, *ibid.* **78**, 2735 (1983).
4. A. G. Zawadzki and J. T. Hynes, Chem. Phys. Lett. **113**, 476 (1985); M. Borkovec and B. J. Berne, J. Chem. Phys. **82**, 794 (1985); A. Nitzan, *ibid.* **82**, 1614 (1985); S. H. Courtney and G. R. Fleming, Chem. Phys. Lett. **103**, 443 (1984); G. Maneke, J. Schroeder, J. Troe, and F. Voss, Ber. Bunsenges. Phys. Chem. (in press).
5. H. Frauenfelder and P. G. Wolynes, Science **229**, 337 (1985).
6. P. G. Wolynes, Phys. Rev. Lett. **47**, 968 (1981); P. Hanggi, H. Grabert, G. L. Ingold, and U. Weiss, *ibid.* **55**, 761 (1985).
7. H. Grabert and U. Weiss, Phys. Rev. Lett. **53**, 1787 (1984); A. I. Larkin and Yu N. Ovchinnikov, Sov. Phys. JETP **59**, 420 (1984); P. Riseborough, P. Hanggi, and E. Freidkin, Phys. Rev. A **32**, 489 (1985).
8. A. O. Caldeira and A. J. Leggett, Ann. Phys. (N.Y.) **149**, 374 (1983); **153**, 445 (1984).
9. H. Grabert, U. Weiss, and P. Hanggi, Phys. Rev. Lett. **52**, 2193 (1984).
10. S. Washburn, R. A. Webb, R. F. Voss, and S. M. Faris, Phys. Rev. Lett. **54**, 2712 (1985); D. B. Schwartz, B. Sen, C. N. Archie, A. K. Jain, and J. E. Lukens, IC-Squids 85, International Conference, Berlin, 1985; (preprint).

Quantum Monte Carlo for Molecules

Although it is at the very heart of theoretical molecular physics, the solution of the Schrödinger equation for many-electron systems remains a difficult computational problem. In recent years conventional techniques have enabled great progress in obtaining molecular properties and potential-energy surfaces.[1] These methods, however, are not always reliable, since large absolute errors occur in the individual calculations of molecular total energies. Frequently, effective cancellation of these errors does occur, enabling reliable calculations of many important molecular properties that are differences of total energies. Nevertheless, the use of these techniques remains largely an "art," built on an empirical body of knowledge.

In the last few years the molecular many-body Schrödinger equation has been solved stochastically via computer simulation[2] using powerful quantum Monte Carlo (QMC) techniques[3] and then applied to the study of molecular problems. By this means highly accurate values for molecular properties, such as reaction barrier heights, energy-level splittings, binding energies, and electron affinities have been obtained,[4] as well as accurate total energies[2] (thus not relying on the cancellation of errors).

In the past year this technique has been extended in a number of significant directions. For example, QMC is being used in the direct calculation of derivatives of the energy with respect to nuclear position.[5] This is very useful for the calculation of potential-energy surfaces, and ultimately for the determination of molecular vibrational frequencies. Accurate expectation values of other properties, such as the moments of the electronic coordinates, are now being calculated. From these one can compute, for example, electric dipole and multipole moments. Furthermore, Monte Carlo techniques are currently being applied to the calculation of the energy of electronically excited states of molecules,[6] which together with the analytic energy derivatives will soon be used to determine excited-state potential-energy surfaces.

The QMC approach as practiced in the above molecular applications shares a special, symbiotic relationship with quantum chemistry: relatively simple approximate wave functions derived from conventional techniques are used to reduce the statistical error inherent in the Monte Carlo approach. Thus, QMC offers a powerful and complementary approach to conventional chemical techniques for the solution of the many-body Schrödinger equation.

Peter J. Reynolds and William A. Lester, Jr., Lawrence Berkeley Laboratory

1. H. F. Schaefer III, *Quantum Chemistry* (Oxford University, New York, 1984).
2. F. Mentch and J. B. Anderson, J. Chem. Phys. **74**, 6307 (1981); P. J. Reynolds, D. M. Ceperley, B. J. Alder, and W. A. Lester, Jr., *ibid.* **77**, 5593 (1982), J. W. Moskowitz, K. E. Schmidt, M. A. Lee, and M. H. Kalos, *ibid.* **77**, 349 (1982); D. M. Ceperley and B. J. Alder, *ibid.* **81**, 5833 (1984).
3. M. H. Kalos, D. Levesque, and L. Verlet, Phys. Rev. A **9**, 2178 (1974); D. M. Ceperley and B. J. Alder, Phys. Rev. Lett. **45**, 566 (1980).
4. P. J. Reynolds, M. Dupuis, and W. A. Lester, Jr., J. Chem. Phys. **82**, 1983 (1985); R. N. Barnett, P. J. Reynolds, and W. A. Lester, Jr., *ibid.* **82**, 2700 (1985); R. N. Barnett, P. J. Reynolds, and W. A. Lester, Jr. (in preparation).
5. B. L. Hammond, P. J. Reynolds, and W. A. Lester, Jr. (in preparation).
6. R. Grimes, P. J. Reynolds, and W. A. Lester, Jr. (in preparation).

Time-Resolved Spectroscopy of Structural Phase Transitions, Vibrating Crystals and Vibrating Molecules

Vibrational motion plays a central role in a great many condensed-phase and molecular phenomena including chemical and structural rearrangements, electronic energy migration and relaxation, heat transfer, and thermal equilibration. Understanding the microscopic dynamics of events such as chemical reactions and structural phase transitions often depends ultimately on knowing what coupled motions occur, and in what sequence, when molecules or crystal lattices vibrate.

Experimental capabilities for characterizing vibrational motion have been improved dramatically by recent developments. The sensitivity and spectral resolution of frequency-domain techniques including IR absorption spectroscopy, Raman spectroscopy of molecular vibrations and optic phonons, and Brillouin spectroscopy of acoustic vibrations have improved steadily.[1] Frequency-domain measurements based on stimulated Raman and Brillouin scattering have produced some remarkable results including high resolution vibrational spectra of large molecules obtained by stimulated Raman gain spectroscopy with ionization detection.[2]

Time-domain transient absorption measurements have been carried out to measure vibrational population lifetimes in bulk media and recently in molecules adsorbed on solid surfaces.[3] Time-domain techniques based on stimulated Raman scattering have yielded accurate measurements of vibrational dephasing times[4] and may permit measurement of lifetimes as well.[5]

Recently, time-domain techniques have been developed which permit spectroscopic observation of vibrating crystal lattices (and other condensed phases) and molecules as they oscillate between undistorted (that is, equilibrium) and vibrationally extended (that is, stretched or bent) configurations. In essence, time-resolved "snapshots"—actually measurements of absorption, scattering, birefringence, or other optical properties—of the vibrating species are recorded at various stages of vibrational distortion. This is especially interesting if, for example, the vibrational mode is a lattice vibration which moves molecules in a crystal toward their positions in an incipient crystalline phase, or is a molecular stretching mode which stretches a bond that is susceptible to thermal or photochemical cleavage.

Time-resolved spectroscopic investigations of solids and other condensed media undergoing acoustic oscillations induced by piezoelectric transducers[6] or by pulsed laser heating[7] have been reported recently. Time-resolved spectroscopy can now be carried out on samples undergoing coherent acoustic, optic, or low frequency molecular vibrational oscillations which are set in motion by crossed ultrashort laser pulses in an "impulsive" stimulated scattering mechanism.[8]

Impulsive stimulated Brillouin scattering (a process in which the electric fields of two ultrashort laser pulses crossed inside a material "impulsively" generate a coherent acoustic wave) was carried out by crossing 2 psec pulses inside the H-bonded crystal, KD_2PO_4 (D-KDP), near its structural phase transition temperature, $T_c = 222$ K.[9] Variably delayed pulses were used to observe coherent acoustic oscillations and acoustically induced dynamic ferroelectric ordering in the time domain. These observations complement earlier frequency-domain results,[10] permitting thorough characterization of the coupled-mode dynamics near the phase transition.

Time-resolved observations of coherent terahertz-frequency optic-phonon oscillations in the organic molecular crystal, α-perylene, were carried out through impulsive stimulated Raman scattering with femtosecond pulses.[11] This opens the door to time-resolved spectroscopy of vibrating molecules[12] as well as simultaneous measurement of phonon dephasing and population lifetimes.

Keith A. Nelson, Massachusetts Institute of Technology

1. See, for example, D.-J. Liu, N. N. Haese, and T. Oka, J. Chem. Phys. **82**, 5368 (1985); G. Pierre, A. Valentin, and L. Henry, Can. J. Phys. **62**, 254 (1984).
2. P. Escherik and A. Owyoung, in Proc. SEICOLS 1985 (Opt. Soc. Am.) (to appear); See also C. Y. She *et al.*, Phys. Rev. A **31**, 3733 (1985).
3. E. J. Heilweil, M. P. Casassa, R. R. Cavanagh, and J. C. Stephenson, J. Chem. Phys. **82**, 5216 (1985).
4. T. J. Kosic, R. E. Cline, Jr., and D. D. Dlott, J. Chem. Phys. **81**, 4932 (1984).
5. R. F. Loring and S. Mukamel, J. Chem. Phys. **83**, 2116 (1985).
6. T. Luty and C. J. Eckhardt, J. Chem. Phys. **82**, 1515 (1985), and references therein.
7. R. J. D. Miller, M. Pierre, T. S. Rose, and M. D. Fayer, J. Phys. Chem. **88**, 3021 (1984).
8. K. A. Nelson, R. J. D. Miller, D. R. Lutz, and M. D. Fayer, J. Appl. Phys. **53**, 1144 (1982).

9. M. M. Robinson, Y.-X. Yan, E. B. Gamble, Jr., L. R. Williams, J. S. Meth, and K. A. Nelson, Chem. Phys. Lett. **112**, 491 (1984); L.-T. Cheng, M. R. Farrar, Y.-X. Yan, and K. A. Nelson (in preparation).
10. R. L. Reese, I. J. Fritz, and H. Z. Cummins, Phys. Rev. B **7**, 4165 (1973).
11. S. De Silvestri, J. G. Fujimoto, E. P. Ippen, E. B. Gamble, Jr., L. R. Williams, and K. A. Nelson, Chem. Phys. Lett. **116**, 146 (1985).
12. Y.-X. Yan, E. B. Gamble, Jr., and K. A. Nelson, J. Chem. Phys. (in press).

Time-Resolved Surface Dynamics

An array of pioneering experiments, which directly probe the dynamics of surface rate processes, constitute major progress in the investigation of chemical physics at surfaces. These experiments include *picosecond* measurements of both vibrational deexcitation,[1] and electronic surface state deexcitation,[2] and *millisecond* measurements of transient populations of surface chemical species with electron energy-loss (vibrational) spectroscopy.[3] Each of these measurements probes a different kinetic event, comprising some of the fundamental rate processes that underlie chemical reactions at surfaces.

In one experiment an InP surface was first excited with a 50-psec pulse of 532 nm laser light (Nd:YAG second harmonic) and then subsequently probed via angle-resolved photoemission (ARUPS).[1] The time separating the pulses was varied with picosecond resolution. The characteristic decay time constant (about 300 psec) for the deexcitation of a normally occupied surface state was found to be consistent with electron diffusion rates into the bulk. This measurement technique was also applied to the study of cleaved silicon. Its application to the deexcitation of surface states associated with adsorbate substrate interactions can be anticipated.

Vibrational deexcitation rates of adsorbates play a key role in determining the disposal of adsorbate energy and consequently the probabilities of following reactive or deexcitation channels in activated reactions. Direct picosecond pump/probe experiments have been carried out to measure the relaxation of vibrationally excited species—such as OH, OD, BOH, NH_2, and OCH_3—adsorbed on SiO_2. The decay rates range from 20 psec to more than 200 psec and depend on the chemical species, the complexity of the local vibrational level structure, and on surrounding species as in the case of solvation. These studies constitute a major portion of the initial understanding of vibrational energy disposal at surfaces.

The measurement of surface reactive processes with a wide dynamic range in time resolution (from 10^{-6} to more than 1 sec) and "chemical" specificity (vibrational spectroscopy) has recently been successfully performed with a new version of conventional electron energy loss spectroscopy.[3] Based on an innovative development in the electron optics design[4] (dispersion compensation), the populations of adsorbed chemical species including intermediates, identified via their vibrational spectra, can be tracked directly with a resolution of less than 1 msec at populations as low as 1% monolayer. This new approach was applied to the adsorption/desorption kinetics of a model system, CO on Cu. In contrast to presently available surface reaction rate detection schemes which require product desorption for detection (allowing one to only *infer* the underlying surface rates), this development permits the surface populations of adsorbates and transient species to be monitored directly in real time.

M. J. Cardillo, AT&T Bell Laboratories, Murray Hill, New Jersey

1. R. Haight, J. Bokor, J. Stark, R. H. Storz, R. R. Freeman, and P. H. Bucksbaum, Phys. Rev. Lett. **54**, 1302 (1985).
2. E. J. Heilweil, M. P. Cassassa, R. R. Cavanagh, and J. C. Stephenson, SPIE **533**, 15 (1985); see also J. Chem. Phys. **82**, 5216 (1985).
3. T. Ellis, L. H. Dubois, S. Kevan, and M. J. Cardillo, Science (to be published).
4. L. H. Dubois and S. Kevan, Rev. Sci. Instrum. **55**, 1604 (1984)

Gas Phase High-Resolution Infrared Studies of Hydrogen Bonded and van der Waals Complexes

Ordinary chemical bonds, hydrogen bonds, and van der Waals bonds form a sequence in which the strength of the bonding decreases by about an order of magnitude from one category to the next. Historically, the hydrogen bond has been extensively studied in condensed phases, where its impact on biological processes is most strongly felt, but it often proved difficult to isolate the effects of the hydrogen bond itself from other solvent effects in such studies. Some time ago spectroscopic studies of gas-phase hydrogen bonded and van der Waals bonded species were initiated in the microwave and radio frequency region. During the past 15 years such studies have yielded a wealth of information on the ground state geometries of these weakly bonded complexes.[1]

The present report focuses on recent studies of gas phase spectra of these same two types of complexes in the infrared region of the spectrum, a region from which we can expect to obtain extensive information concerning the strength (resistance to bending and stretching) and dynamics (vibrational trajectories) of the weak bond, as well as information on vibrational energy flow processes within the molecule. Indeed, it may well turn out that these processes, and the related question of predissociation as the prototypical unimolecular reaction, can most easily be understood theoretically in these weakly bound complexes, where the quantum mechanical description of the preparation of the lowest dissociating state often involves absorption of a single photon and excitation of a single quantum of one vibrational degree of freedom.

A series of difference frequency laser studies in the region from 3000 to 4000 cm^{-1} ($8066\ cm^{-1} = 1$ eV) has been carried out at NBS in Washington by A. S. Pine and collaborators. These include elegant experimental studies in a cooled static cell and extensive assignment and intepretation of spectra of $(HF)_2$, $(HCl)_2$, and Rg · HCl, where Rg represents a rare gas atom.[2]

F-center laser studies in the same spectral region have been obtained by R. E. Miller and collaborators (Canberra) on $(CO_2)_2$, $(N_2O)_2$, and $(C_2H_2)_2$. Problems associated with this very high resolution technique have so far prevented assignment and interpretation of these beautiful spectra.[3] Using an F-center laser and cooled static cell conditions J. W. Bevan (Texas A&M) and collaborators have carried out studies on vibrational bands in HCN · HF and OC · HF. Bevan's work is particulary important for energy flow and predissociation modeling, because it demonstrates the possibility of extracting information on anharmonic interactions between vibrational modes from infrared transitions originating in excited vibrational states of these weakly bound complexes.[4]

Spectra obtained by B. J. Howard (Oxford) and collaborators in the 2100 cm^{-1} region (CO and NO stretches) for various complexes using a diode laser spectrometer and a pulsed nozzle molecular source, are important because they indicate that vibrational energy regions other than 3000–4000 cm^{-1} are now experimentally accessible.[5]

None of the spectra mentioned above directly study the low frequency vibrations arising from the weak hydrogen bond or van der Waals bond holding the complex together, and it is precisely these vibrations that can be expected to give the most information on the nature of such bonds. First steps in this direction have been taken at Harvard by Klemperer and collaborators[6] and at Berkeley by R. J. Saykally and collaborators,[7] where far infrared rotation–vibration transitions in bending vibrational region for Ar · HCl have been investigated.

Jon T. Hougen, National Bureau of Standards

1. T. R. Dyke, in *Hydrogen Bonds, Topics in Current Chemistry*, edited by F. L. Boschke (Springer, New York, 1984), Vol. 120.
2. A. S. Pine, W. J. Lafferty, and B. J. Howard, J. Chem. Phys. **81**, 2939 (1984).
3. R. E. Miller, F. F. Vohralik, and R. O. Watts, J. Chem. Phys. **80**, 5453 (1984).
4. E. K. Kyro, P. Shoja-Chaghervand, K. McMillan, M. Eliades, D. Danzeiser, and J. W. Bevan, J. Chem. Phys. **79**, 78 (1983).
5. G. Hayman, J. Hodge, B. Howard, T. Dyke, and J. Muenter, Symposium on Molecular Spectroscopy, Columbus, Ohio 1985.
6. M. D. Marshall, A. Charo, H. O. Leung, and W. Klemperer, Symposium on Molecular Spectroscopy, Columbus, Ohio, 1985.
7. D. Ray, R. L. Robinson, D. H. Gwo, and R. J. Saykally, Symposium on Molecular Spectroscopy, Columbus, Ohio, 1985.

CONDENSED MATTER PHYSICS

Condensed matter physics is concerned with the fundamental physical processes that take place in solids and fluids. This field, which is of both basic scientific interest and technological importance, continues to be one of the most active areas of physics research. Described herein are five newsworthy developments in condensed matter research that have occurred during the past year.

When a beam of electrons is split, and then recombined, in such a way that the separate paths of the electrons surround a region containing magnetic flux, interference patterns that are periodic with a period equal to the magnetic flux are observed. This effect, first predicted by Aharonov and Bohm in 1959, is a consequence of the dependence of the phases of the electrons on the magnetic vector potential. As described by Webb, Washburn, and Present, the Aharonov–Bohm effect has recently been observed in experiments on disordered submicron-sized single rings of gold at temperatures as low as 10 mK. The effect is manifested as oscillations, periodic in h/e, in the magnetoresistance of the rings, even though the mean free path for elastic scattering of the electrons is much smaller than the dimensions of the rings.

Although a great deal of progress has been made in understanding the physical properties of glasses, the local microscopic structure of glasses is still not well understood. Sethna discusses a crystalline system $(KBr)_{1-x}(KCN)_x$ that freezes into a disordered "orientational glass" state where football-shaped cyanide ions, which randomly replace bromines in the lattice, have two orientations differing by 180°. The resultant "two level system," which has a distribution of barrier heights that hinder the 180° rotations of the cyanide ions, is responsible for both the low frequency and low temperature "glassy" behavior of this crystalline material.

An important application of neutron scattering is the determination of the positions and orientations of magnetic moments in magnetically ordered materials, such as the unusual spiral configurations of magnetic moments found in many of the magnetic rare earth elements. X-ray diffraction, the common method for deriving the crystal structure of a substance, has not previously been used for magnetic structure determination because the ratio of magnetic to charge scattering is less than about 10^{-5}. Recently, however, the intense x-ray beams that are now available from synchrotron sources have enabled researchers to investigate the incommensurate magnetic spiral structure of holmium metal by means of x-ray diffraction. As described by Gibbs and Moncton, this work has uncovered a new behavior of the temperature dependence of the period of the magnetic spiral in holmium which, in turn, has stimulated the development of a new model for the magnetic structure of rare earths.

As every solid state physicist knows, crystals are allowed to have only certain types of translational and orientational symmetries. Thus it was very surprising when electron diffraction measurements on a rapidly quenched alloy of aluminum and manganese revealed a pattern of sharp spots with icosohedral symmetry, a symmetry that is precluded in crystals. According to Steinhardt, a possible explanation for this remarkable behavior is that the alloy is an example of a "quasicrystal," a new phase of solid matter that is *quasiperiodic*, rather than periodic like a crystal, with atomic arrangements of two or more types of structural units that repeat in a sequence defined by a sum of periodic functions with incommensurate periods.

During the 1930's, the electrical resistivity of many "pure" metals such as copper and gold was found to exhibit a minimum at low temperatures in the vicinity of the boiling point of liquid hydrogen (20.4 K). The theoretical explanation of this effect was given in 1964 by Kondo, who showed that for metals containing small concentrations of transition metal impurities, such as iron, which carry localized magnetic moments, there is a contribution to the electrical resistivity at low temperatures that varies as the logarithm of the temperature. The calculation is not valid at temperatures far below a characteristic temperature, known as the Kondo temperature, and requires a negative (antiferromagnetic) exchange interaction between the spins of the conduction electrons and the spins of the transition metal impurities. As discussed by Wilkins, the complete theoretical description of the "Kondo effect" at all temperatures has been developed only recently, more than 20 years after the appearance of Kondo's original paper. A formidable challenge that remains is the extension of this theory to a *lattice* of magnetic moments in a metal.

M. Brian Maple, University of California, San Diego

Quasicrystals

For decades physicists believed that the atomic structure of a pure solid must be either crystalline or glassy. This basic tenet of solid state physics has been shattered recently with the discovery of a new solid that is neither. The new solid, discovered by physicists working at the National Bureau of Standards, is an alloy (see Fig. 1) formed by rapidly cooling a mixture of aluminum and manganese to form a metastable solid composed of micron-size dendritic grains.[1,2] When electrons are diffracted from the solid, they scatter to form a set of sharp spots arranged in a pattern with icosahedral symmetry (see the cover figure). As in a crystal, the sharp spots mean that the structure has long range translational order—that is, given the positions of a few atoms in the structure, the positions of the remaining atoms can be reliably predicted. The symmetry of the spot pattern means that the structure also has icosahedral orientational order—that is, the orientation of neighboring atoms or clusters is constrained (on average) to be along the symmetry axes of an icosahedron. The icosahedron is a regular polyhedron with 12 vertices and 20 identical triangular faces (the centers of the pentagons on the surface of a soccer ball lie at the vertices of an icosahedron).

The result is startling because, according to the rigorously proven theorems of crystallography, icosahedral symmetry is disallowed for crystals. A possible explanation for the observed diffraction pattern within the bounds of crystallography involves multiple scattering from twinned microcrystallites defined, perhaps, by unit cells containing many atoms. However, other evidence from high-resolution electron micrographs, x-ray diffraction, and dark field imaging does not support this model.

The leading explanation, first proposed by theorists at the University of Pennsylvania,[2,3] is that the alloy is an example of a new class of ordered atomic structures which they termed "quasicrystals." Quasicrystals represent a new phase of solid matter which exhibits long range orientational order and translational order, like a crystal. Quasicrystals, however, are quasiperiodic rather than periodic—the atoms are arranged in two or more types of structural units which repeat in a sequence defined by a sum of periodic functions with incommensurate (relatively irrational) periods. Clusters of the structural units appear in recurring motifs on every length scale, but there is no regular repeating pattern.

The inspiration for quasicrystals derived from a study of a set of nonperiodic, two-dimensional tilings developed by Oxford physicist Roger Penrose.[4] The tilings are composed of

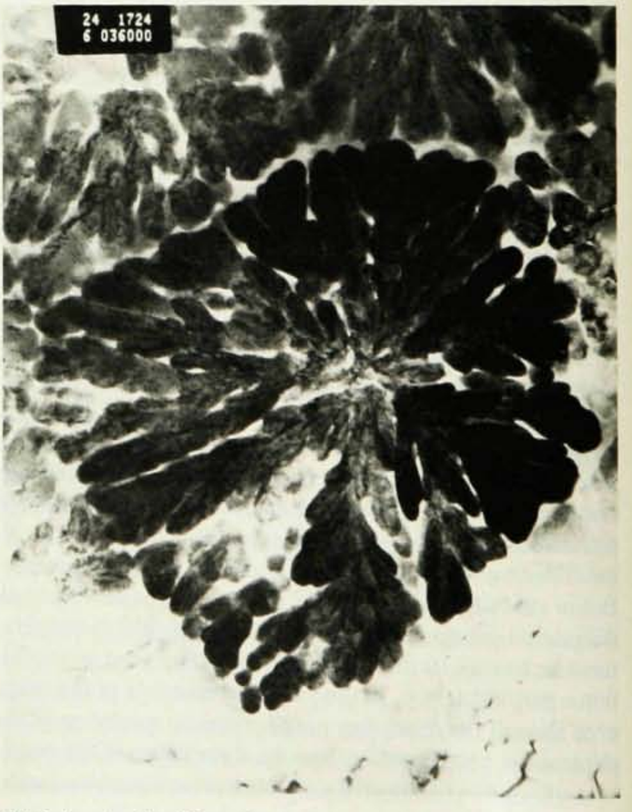

FIG. 1. A grain of rapidly cooled aluminum–iron alloy possessing an icosahedral rotation symmetry.

two fundamental shapes arranged in a pattern with fivefold orientational order, which is also disallowed for crystals. The intriguing tilings had attracted the attention of numerous mathematicians and physicists, some of whom suggested the possibility of atomic structures analogous to Penrose tilings.[2] However, only when the full symmetries, especially the quasiperiodicity, were identified could schemes for constructing analogs with other symmetries in other dimensions be developed, including a three-dimensional analog with icosahedral symmetry.[3,5] In general, quasicrystal lattices with arbitrary orientational symmetry are possible.

The diffraction pattern of an ideal quasicrystal consists of a pattern of true Bragg peaks (point spots), a signal of the translational order, arranged in a pattern that reflects the orientational symmetry. Owing to the presence of incommensurate periodicities in the structure, the peaks densely fill the pattern, although the amplitudes of most peaks are too small to be observed experimentally. The match between the computed diffraction pattern for an ideal icosahedral quasicrystal and the experimentally observed pattern led to the proposal that the new alloy is a quasicrystal.[3]

In a very useful alternative approach, several groups[5,6] have shown that quasicrystal lattices can be generated by various projections from higher dimensions; for example, an icosahedral lattice can be generated by projecting a six-dimensional hypercubic periodic lattice onto three dimensions. This mathematically elegant approach allows a straightforward calculation of Bragg peak intensities. In yet another description based on Landau's theory of phase transitions, the atomic structure is described as a set of mass density waves with adjustable magnitudes and phases. This method lends itself naturally to calculations of the structural stability, thermodynamics, elasticity, and occurrence of defects in the quasicrystal phase.[6,7]

The evidence that the new alloy is a quasicrystal is not yet totally conclusive. Direct measurements of the translational order indicate a finite correlation length of only a few hundred angstroms, although this is most likely due to strain or defects in the samples.[6,8] The immediate challenge to experimentalists is to produce alloys with larger and more perfect grains, both to resolve the issue and to accurately measure physical properties. Efforts in this direction have already led to a growing list of candidate quasicrystal alloys, including reports of alloys with other symmetries disallowed for crystals. The challenge to theorists is to develop the mathematical tools necessary to analyze the physical properties of quasicrystals. Whether or not the alloy proves to be a quasicrystal, Pandora's box has been opened: Physicists should not be satisfied until a quasicrystal atomic structure is positively identified or a physical principle is found to explain why nature cannot take advantage of this marvelous possibility.

Paul J. Steinhardt, University of Pennsylvania

1. D. S. Shechtman, I. Blech, D. Gratias, and J. W. Cahn, Phys. Rev. Lett. **53**, 1951 (1984).
2. Phys. Today **38**, 20 (February, 1985).
3. D. Levine and P. J. Steinhardt, Phys. Rev. Lett. **53**, 2477 (1984).
4. M. Gardner, Sci. Am. **236**, 110 (January 1977).
5. P. Kramer and R. Neri, Acta Crystallogr. Sect. A **40**, 580 (1984); V. Elser, Bell Laboratories preprint (1985); P. A. Kalugin, A. Kitaev, and L. Levitov, JETP **41**, 119 (1985); M. Duneau and A. Katz, Palaiseau preprint (1985).
6. News and Views, Nature **315**, 178 (1985).
7. D. N. Mermin and S. M. Troian, Phys. Rev. Lett. **54**, 1524 (1985); P. Bak, *ibid.* **54**, 1517 (1985); D. Levine, T. C. Lubensky, S. Ostlund, S. Ramaswamy, P. J. Steinhardt, and J. Toner, *ibid.* **54**, 1520 (1985); P. A. Kalugin *et al., ibid.*; D. R. Nelson and S. Sachdev, Harvard preprint (1985).
8. P. Bancel, P. A. Heiney, P. W. Stephens, A. I. Goldman, and P. M. Horn, Phys. Rev. Lett. **54**, 2422 (1985).

Aharonov–Bohm Effect in Disordered Metals

A number of remarkable magnetoconductance phenomena in single, ultrasmall, normal-metal rings have been uncovered recently in a series of experiments at the IBM T. J. Watson Research Center. The phenomena include a resistance that oscillates for more than 1000 cycles with applied magnetic field asymmetries between positive and negative field, and large-amplitude, reproducible but "aperiodic" long-wavelength resistance changes with applied field.

What makes these effects so novel is that they appear to occur in a single small ring but not in suitably averaged measurements on large collections of small rings. This suggests that these phenomena might be neither microscopic nor macroscopic, but rather characteristically "mesoscopic" in nature, having properties that appear precisely because of the intermediate size of the system (with maximum dimensions comparable to the inelastic scattering length).

These discoveries were made in the context of studies of the well known Aharonov–Bohm[1] effect: If a beam of electrons is split and then recombined so that the separate paths surround an area containing magnetic flux, then the resulting interference pattern is sensitive to that magnetic field. Physically observable effects include oscillation of the electron current with a period equal to the flux h/e, where h is Planck's constant and e is the charge of the electron.

Although the flux-periodic effects were confirmed in electron-beam experiments[2] almost immediately after Aharonov's and Bohm's predictions, the question of whether or not they could be seen in disordered materials has been debated for more than 25 years. Last spring, physicists at IBM provided convincing experimental confirmation of magnetoresistance oscillations with a period h/e in small, disordered, single rings of gold.[3] The experiments, conducted at temperatures as low as 0.01 K, were made possible by the ability to fabricate ultrasmall structures (largest dimension less than a micron) using a combination of scanning transmission electron microscopy and contamination-resist technology (see Fig. 2).

The observation of h/e periodic effects in rings requires that the phases of the electrons be preserved during their trip along the entire sample length. That is, the phase coherence length must be larger than the diameter of the ring. This

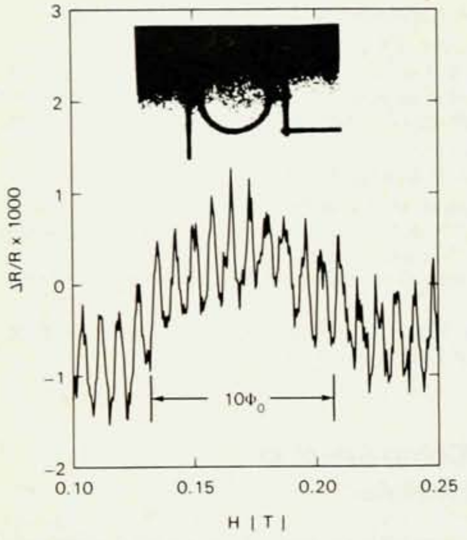

FIG. 2. Magnetoresistance of an 825 nm diameter ring as a function of applied magnetic field strength. The oscillations have a period equal to h/e (0.0078 T). The inset is an electron micrograph of the ring; the width of the wires forming the device is 41 nm.

condition was satisfied by using gold rings with very small diameters at very low temperature. The fact that the elastic scattering length (the distance electrons typically travel before scattering elastically) for gold was much shorter than the circumference of the rings proved that the elastic scattering processes responsible for the residual resistivity at $T = 0$ do not destroy the phase coherence necessary for the observation of the Aharonov–Bohm effect. One important result was that the h/e resistance oscillations persisted unattenuated for more than 1000 periods in magnetic fields greater than 8 T (80 kG). The oscillations were superimposed upon a randomly fluctuating background magnetoresistance with amplitude comparable to the h/e oscillations. Similar aperiodic background fluctuations were also observed in single wires whose lengths were shorter than the phase coherence length.[4] These background effects are now believed to arise from the presence of the magnetic field and the occurrence of an Aharonov–Bohm effect in the region where the electrons are confined.[5] Both the h/e oscillations and the random background fluctuations are not symmetric about zero magnetic field and are in qualitative agreement with recent theoretical predictions.[6,7]

Flux-periodic effects in condensed-matter systems are not new. Magnetoresistance oscillations periodic in h/e were observed for a few oscillation periods at low magnetic fields in 1978 in experiments on small, single-crystal cylinders of bismuth.[8] Superconducting systems are well known for effects periodic in the flux $h/2e$. These include flux quantization, persistent currents, and the Josephson effects. Prior to the IBM work, resistance oscillations in small diameter (1 μm), normal-metal cylinders were reported,[9] but with a period of $h/2e$, half that of the usual Aharonov–Bohm period. Similar effects have since been seen by numerous other groups using both long cylinders and arrays of rings.[9] One feature common to all those normal-metal experiments in which $h/2e$ effects were observed is that at least one dimension of the sample was much longer than the phase coherence length. Thus the measured oscillations in those experiments represent the average behavior over a large number of uncorrelated regions of the sample.

The reason h/e oscillations were not observed there is that the phase of the h/e oscillations depends upon the details of scattering processes within each correlated section of the sample. Consequently, the h/e oscillations average to zero for a very long device. The $h/2e$ process, on the other hand, results from electrons that retrace their paths, effectively doubling the path length and halving the period, with the phase of the oscillations constrained to be a maximum at zero field.[9] The $h/2e$ oscillations survive averaging over many incoherent regions of the sample and therefore can be observed in large cylinders. However, the amplitudes of these oscillations are quenched by very small magnetic fields (less than 0.01 T in general).

The IBM experiments confirmed a series of theoretical predictions[6] that the fundamental period in all normal-metal systems should be h/e, with $h/2e$ behavior occurring in general as a harmonic. The observation of unattenuated h/e periodic oscillations, asymmetry, and aperiodic background fluctuations are all manifestations of the fact that the phase coherence length is larger than all the dimensions of the samples and that the transport properties reflect the bare quantum mechanical transmission coefficient of the structure. These are only the first results in these quantum mechanically, coherent normal-metal systems, and it is clear that much more physics can be expected from additional research in this area.

R. A. Webb, S. Washburn, and G. Present,
IBM T. J. Watson Research Center

1. Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).
2. R. G. Chambers, Phys. Rev. Lett. **5**, 3 (1960).
3. R. A. Webb, S. Washburn, C. P. Umbach, and R. B. Laibowitz, Phys. Rev. Lett. **54**, 2696 (1985); S. Washburn, C. P. Umbach, R. B. Laibowitz, and R. A. Webb, Phys. Rev. B (in press).
4. C. P. Umbach, S. Washburn, R. B. Laibowitz, and R. A. Webb, Phys. Rev. B **30**, 4048 (1984).
5. A. D. Stone, Phys. Rev. Lett. **54**, 2692 (1985).
6. M. Buttiker, Y. Imry, R. Landauer, and S. Pinhas, Phys. Rev. B **31**, 6207 (1985), and references cited therein.
7. M. Buttiker and Y. Imry, J. Phys. C **18**, L467 (1985).
8. N. B. Brandt, *et al.*, Sov. J. Low Temp. Phys. **8**, 358 (1982), and references cited therein.
9. See the review by Yu. V. Sharvin, Physica B **126**, 288 (1984).

Glassy Crystals

The powerful theoretical and experimental methods used to understand the structure and properties of crystals are largely useless in explaining glasses. The local microscopic structure of glasses is still controversial; answers to basic questions such as why is a glass solid? (or even is a glass solid?) remain mysterious to physicists. Thus the discovery that certain *crystalline* systems have many properties characteristic of glasses is a valuable opportunity for testing our models of glassy behavior.

Glasses are amorphous-like liquids, but are rigid-like crystals. Unlike a crystal, in which each atom has a set position, a glass will have a completely different configuration of atoms each time it is formed. Sometimes atoms or local groups of atoms will have two low-energy configurations, and can shift between them. Some of these atoms shift much faster than others, leading to a broad distribution of relaxation times. Thus, when put under an external stress a glass will gradually continue to bend, albeit more and more slowly, for centuries. These "two-level systems" are also responsible for the universal low temperature properties shared by all configurational glasses.[1] (Glasses have specific heats proportional to temperature and thermal conductivities proportional to T^2, in contrast to insulating crystals where both properties vary as T^3 for low temperatures T.) These ideas depend in no way on the detailed structure of the materials; they naturally apply to all glasses. However, the microscopic configurations of the two-level systems have remained a mystery, and progress in understanding the low frequency relaxation has been slow.

The mixed crystal $(KBr)_{1-x}(KCN)_x$ shares many properties with glasses; however unlike glasses its structure is well understood. When the relative cyanide concentration x lies 0.1 and 0.6 the crystal freezes into a disordered "orientational glass" state. This state has a broad distribution of relaxation times[2] and all the universal low temperature properties of glasses.[3] The samples are cubic single crystals with a sodium chloride structure, football-shaped cyanide ions randomly displacing bromines in the lattice. Strong cyanide–cyanide elastic forces freeze the long axes of the cyanides into position, but each has two low-energy states (given by swapping the carbon and nitrogen ends of the ion). Because each cyanide has a different set of neighbors, some can flip over more easily than others: there is a distribution of barrier heights hindering the 180° rotations. The broad distribution of relaxation times exhibited by the dielectric loss measurements[2] comes from random thermal rotations of cyanide ions over these barriers.[4] The time-dependent specific heat (one of the universal low temperature properties of glasses) comes from quantum tunneling of these ions through the same barriers.[5]

Thus, cyanides which reorient by 180° form the "two level systems" in $(KBr)_{1-x}(KCN)_x$, and provide a unified explanation of both its low frequency and low temperature glassy behavior. We do not have a general theory of glasses, but we understand more clearly the universal glassy behavior of a particular salty material. We hope and expect that further study of glassy crystalline systems will resolve some of the other mysteries about glasses.

James P. Sethna, Cornell University

1. R. C. Zeller and R. O. Pohl, Phys. Rev. B **4**, 2029 (1971); P. W. Anderson, B. I. Halperin, and C. M. Varma, Philos. Mag. **25**, 1 (1972); W. A. Phillips, J. Low Temp. Phys. **7**, 351 (1972).
2. F. Luty and J. Ortiz-Lopez, Phys. Rev. Lett. **50**, 1289 (1983); N. O. Birge, Y. H. Jeong, S. R. Nagel, S. Bhattacharya, and S. Susman, Phys. Rev. B **30**, 2306 (1984).
3. J. J. De Yoreo, M. Meissner, R. O. Pohl, J. M. Rowe, J. J. Rush, and S. Susman, Phys. Rev. Lett. **51**, 1050 (1983); D. Moy, J. N. Dobbs, and A. C. Anderson, Phys. Rev. B **29**, 2160 (1984).
4. J. P. Sethna, S. R. Nagel, and T. V. Ramakrishnan, Phys. Rev. Lett. **53**, 2489 (1984); I. Kanter and H. Sompolinsky (to be published).
5. M. Meissner, W. Knaak, J. P. Sethna, K. S. Chow, J. J. De Yoreo, and R. O. Pohl (to be published).

Magnetic X-Ray Scattering

An x-ray incident on an electron is scattered both by the electron's charge and by its magnetic moment. Charge scattering is the dominant mechanism and is the basis for structural investigations of condensed matter by x-ray diffraction. In 1970 Platzman and Tzoar[1] first suggested the possibility of studying magnetic structures directly using x rays. Subsequently, there have been experimental[2] and theoretical[3] developments, but progress to date has been limited by the fact that even in the most favorable cases, the ratio of magnetic-to-charge scattering is less than about 10^{-5}. The advent of intense x-ray beams from synchroton sources has recently made it possible to measure such weak signals easily and has led to a new understanding of rare earth magnetism.

In this work Doon Gibbs and co-workers made magnetic x-ray scattering measurements of the element holmium at the Stanford Synchrotron Radiation Laboratory.[4] Ho has a hexagonal close-packed crystal structure and a large spontaneous magnetic moment per atom. Below a temperature of 131 K Ho is a simple "spiral antiferromagnet," in which the moments are ferromagnetically aligned within the basal plan (the plane perpendicular to the long axis in the crystal), but rotate from plane to plane with a turn angle varying between 50°/layer near 130 K and 30°/layer near 20 K. Within the hexagonal planes there are six equivalent easy directions along which the moments tend to align. The detailed magnetic structure and period at a given temperature T are determined by the competition among exchange, lattice, and magnetoelastic forces.

Using a newly developed polarization analyzer for distinguishing charge and magnetic scattering it was shown that certain previously unobserved effects arose from modulated magnetoelastic charge scattering. An interpretation of these results emerged from a model of the magnetic structure for rare earths based on the concept of "spin slips."[5] Briefly, spins are arranged in pairs associated with the six easy directions to form a spiral of doublets. A single spin slip in the magnetic spiral is created by associating one less spin to an easy direction. In Ho the lattice distorts at slip positions, which gives rise to the additional charge "satellites" observed in the x-ray diffraction pattern. Considered in this way spin slips are analogous to domain walls or solitons.

The existence and location of the additional satellites observed in the x-ray data have a natural explanation as charge scattering from the spin-slip distribution.[4] The spin-slip model also explains anomalous higher harmonic satellite intensities observed by neutron diffraction.

Future prospects for magnetic x-ray scattering experiments using synchrotron sources are bright. Intrinsic properties of the scattering cross section, such as possible spin-dependent resonance and interference effects, are still largely unexplored.[2] Utilizing a circularly polarized incident beam it may be possible to separate the orbital and spin angular momentum contribution to the cross section.[3]

In addition, high brilliance synchrotron sources will make feasible experiments that are currently outside the traditional areas accesible to magnetic neutron scattering or spin polarized electron scattering. These include, for example, magnetic x-ray scattering at resolutions approaching 10^{-4} Å^{-1} and magnetic x-ray scattering from small-volume materials such as films, artificial superlattices, and perhaps ultimately from surfaces. Such developments may finally provide a direct structural probe of surface magnetism.

Doon Gibbs and D. E. Moncton,
Brookhaven National Laboratory

1. P. M. Platzman and N. Tzoar, Phys. Rev. B **2**, 3556 (1970).
2. F. de Bergevin and M. Brunel, Phys. Lett. A **39**, 141 (1972); Acta Crystallogr. Sect. A **37**, 314 (1981); M. Brunel and F. de Bergevin, *ibid.* **37**, 324 (1981); M. Brunel, G. Patrat, F. de Bergevin, F. Rousseau, and M. Lemmonnier, *ibid.* **39**, 84 (1983); D. Gibbs, D. E. Moncton, and K. L. D'Amico, J. Appl. Phys. (to be published).
3. M. Blume, J. Appl. Phys. (to be published); P. M. Platzman, *ibid.* (to be published).
4. D. Gibbs, D. E. Moncton, K. L. D'Amico, J. Bohr, and B. Grier, Phys. Rev. Lett. **55**, 234 (1985).
5. J. Bohr, D. Gibbs, and D. E. Moncton (to be published).

Solution of the Kondo Problem (At Last)

The presence of magnetic impurities in metallic hosts (for example, Fe in Cu or Ce in LaB_6) profoundly changes their physical properties. Most strikingly, the resistivity per impurity rises as the temperature is lowered, contrary to the normal expectation that scattering processes should "turn off" as the thermal excitations are decreased.

The idealized version of this problem, that of a single magnetic impurity in a metal, is referred to as the "Kondo Problem," named for J. Kondo of the University of Tokyo, and has been of interest to theorists since the early 1960's. Although partial solutions of the Kondo problem have twice appeared,[1] only in the last two years have developments occurred that permit a systematic calculation of all properties and, what is more important, provide a physical understanding of these properties.

Many features of the solution for the dilute impurity case seem relevant for more concentrated systems (especially alloys containing rare earth elements) that have attracted attention under the label of mixed valence or heavy fermion systems[2] (see *Physics News in 1984*, p. S20). The behavior of a large group of cerium-based systems demonstrated a set of common features needing explanation, such as an enhanced specific heat and an enhanced temperature-independent magnetic susceptibility.

Central to the explanation of these features was the recognition that the large degeneracy (the number of states with the same energy) N of the f-orbital electrons of cerium might be used to develop a mathematical expression for the properties in terms of a convergent expansion in inverse powers of N. What makes the problem of even a single impurity so technically difficult is that while the cerium f-orbital state has an N-fold degeneracy, it can only be singly occupied because the Coulomb repulsion between electrons is very large when they are placed in the localized f-orbital state. Overcoming this technical difficulty has taken more than 20 years and entailed the use of every important development in theoretical physics.

The first breakthrough[4] came with the development of a method for calculating the density of electronic states. In addition to the singly filled f orbital below the Fermi level (the highest filled level) and an empty level far above, there was a sharp peak just above the Fermi level. This peak, called a Kondo or Abrikosov–Suhl resonance, is a true, many-body effect (that is, it has no explanation in terms of noninteracting particles).

The early work also predicted that the enhanced specific heat and susceptibility resulted from the Kondo peak. However, the initial formulation could not be used to calculate the temperature dependence of the properties. This difficulty was soon overcome by a simultaneous development of several mathematical formalisms, all of which led to the same set of integral equations.[5] Numerical solution of these equations could be used to compute all measured properties. In addition to the specific heat and susceptibility (which had been calculated by earlier methods[1]), theorists were able to compute the resistivity, other transport properties, and neutron scattering behavior.[6] For example, in the case of one alloy (dilute Ce in LaB_6) it has proved possible to fit four different properties, each measured over decades of temperature, with a single parameter: the position of the Kondo resonance.[7] This universality of behavior had long been expected.

John Wilkins, Cornell University

1. K. G. Wilson, Rev. Mod. Phys. **47**, 773 (1975); N. Andrei, K. Furuya, and J. H. Lowenstein, *ibid.* **455**, 331 (1983); Phys. Today **34**, 21 (May, 1981).
2. See, for example, G. R. Stewart, Rev. Mod. Phys. **56**, 755 (1984); *International Conference on Valence Fluctuations*, edited by E. Müller-Hartmann, B. Roden, and D. Wohlleben, J. Magn. Magn. Mater. **47**, 48 (1985).
3. P. W. Anderson, in *Valence Fluctuation in Solids*, edited by L. M. Falicov, W. Hanke, and M. B. Maple (North-Holland, Amsterdam, 1981), p. 451.
4. O. Gunnarsson and K. Schönhammer, Phys. Rev. Lett. **50**, 604 (1983); Phys. Rev. B **28**, 4315 (1983).
5. P. Coleman, Phys. Rev. B **29**, 3035 (1985); H. Keiter and G. Czycholl, J. Magn. Magn. Mater. **31**, 477 (1983); Y. Kuramoto, Z. Phys. B **53**, 37 (1983); F. C. Zhang and T. K. Lee, Phys. Rev. B **28**, 33 (1983); N. Grewe, Z. Phys. **52**, 193 (1982); H. Keiter and J. C. Kimball, Int. J. Magn. **1**, 233 (1971).
6. H. Kojima, Y. Kuramoto, and M. Tachiki, Z. Phys. B **54**, 293 (1984); D. L. Cox, N. E. Bickers, and J. W. Wilkins, J. Appl. Phys. 57, 230 (1985).
7. N. E. Bickers, D. L. Cox, and J. W. Wilkins, Phys. Rev. Lett. **54**, 230 (1985).

CRYSTALLOGRAPHY

The biggest news in crystallography in 1985 was the award of the Nobel Prize to Jerome Karle of the Naval Research Laboratory in Washington, D.C. and Herbert Hauptman of the Medical Foundation of Buffalo. They shared the prize for their revolutionary development, about 30 years ago, of direct methods for the crystal structure determination of chemicals, drugs, hormones, and antibiotics. Their work plays a major role in allowing the structure determination of the tens of thousands of structures contained in the Cambridge Structural Database (see the article below). Both men are still active today in efforts to apply similar techniques to the determination of protein structures, a research area that may undergo a revolution (also described in an article below) in the next decade.

X-ray crystallographic data are playing an ever expanding role in molecular biophysics and pharmacology. Primary factors responsible for this growth include rapidly developing technologies, the feasibility of macromolecular engineering, and the continued growth of structural data-bases. The increased availability of synchrotron radiation sources and area detectors will be producing more and better intensity data on proteins.

Larger computers and more powerful mathematical techniques to automate the process of structure solution will lead to an exponential increase in our knowledge of protein and macromolecule structure. Advances in computer graphics will allow more rapid analysis and digestion of this information so that new insights into the structural basis for all biological processes will pave the way for the design of drugs and macromolecules to rectify metabolic flaws and combat disease.

William Duax, Medical Foundation of Buffalo

Technological Advances

In the past 25 years the time required to determine the crystal structure of an average organic molecule has accelerated from years to days. This accounts for the presence of 45,000 structures in the Cambridge Structural Database. This avalanche of reliable data on molecular structure has contributed immeasurably to our understanding of the properties of atoms and molecules. We have reliable sources from which to predict characteristic bond lengths, valence angles, and nonbonding contacts for almost all atoms of practical interest.

Although the speed with which the crystal structures of proteins are determined has also been accelerated, an average protein structure determination still takes 2–3 years. The limiting factors in this process are preparation of suitable crystals doped with heavy atoms needed to permit structure determination, the availability of sufficient supply of stable single crystals for a data collection process that often requires months, if not years, and computing power capable of refining thousands of observed data.

As a result of recent technological advances many of these drawbacks of protein structure analyses are about to disappear and in the next few years it may be possible to complete x-ray structure determination within 4 to 6 months of the time that single crystals of the native protein are prepared. The data collection process is being accelerated by the use of synchrotron radiation sources[1] and area detectors. Because synchrotron radiation is hundreds of times more intense than normal x-ray radiation, smaller crystals and much shorter exposure times can be used to obtain intensity data that often exceeds the data resolution possible from normal sources. By using film techniques a full set of intensity data on a native crystal of a 40,000 molecular weight protein can be collected in less than a week using just a few crystals.

The thousands of diffraction intensities gathered on dozens of films using a synchrotron source must be read on a microdensitometer and merged into an internally consistent set of relative intensities. This process takes far longer than the actual data collection. However, sophisticated software to accomplish this task is gaining wide distribution and the availability of more powerful computers indicate that this barrier is also about to tumble.[2] Area detectors are multiwire electrical devices that will further accelerate the pace of protein data collection.[3] Area detectors allow the simultaneous collection of hundreds of intensities in a digital form, thereby eliminating the time consuming step of film reading.

Advances in the area of methods of structure determination will also contribute to this explosion. The determination of a crystal structure depends upon determining the phases of a significant number of the observed intensities. It has been clearly demonstrated that the intensities contain information about their phases and techniques for extracting phase information from the intensities have been developed over the past 30 years. Because of the phenomenal success of these techniques they have become the method of choice in solving small molecule structures. Now it would appear that some of the strength of these techniques can be applied to protein studies so that semiautomated solution of the phase problem using data from just one heavy atom derivative in combination with the native data,[4] data sensitive to anomolous scatters in the native protein,[5-7] and/or data gathered from tuneable wavelength sources[8] can be expected to contribute to much faster determination of protein structures and the elimination of the need for many heavy atom derivatives.

The challenge of protein crystal structure analysis that has proven least vulnerable to attack is the initial step, that of growing diffraction quality single crystals. Protein and small peptide growth has generally been considered a branch of witchcraft rather than of science. As other aspects of protein crystallography become more routine, investigators are turning their attention to developing reliable procedures for protein crystal growth. Topics addressed at the first International Conference on Protein Crystal Growth at Stanford in August of 1985 included crystallization under microgravity environment, measurement of concentration gradients, effects of polyethylene glycol, and high salt concentration on crystallization, and the mapping of solution properties during crystal growth. Experiments involving the growth of protein crystals aboard Spacelab 2 in the summer of 1985 generated a debate about the merits of such experiments.[9] Charles Bugg of the University of Alabama, one of the proponents of the experiments suggested that crystal growth without gravitational effects and convection currents had the advantage of permitting crystals to remain suspended in a homogenous medium during growth.

William Duax

1. T. J. Greenhough and J. R. Hellievelle, Prog. Biophys. Mol. Biol. **41**, 67 (1983).
2. Chem. Eng. News, August 12, 1985.
3. S. C. Harrison, Nature **309**, 408 (1984).
4. H. Hauptman, Acta Crystallogr. Sect. A **38**, 289 (1982).
5. W. A. Hendrickson and M. M. Teeter, Nature **290**, 107 (1981).
6. H. Hauptman, Acta Crystallogr. Sect. A **38**, 632 (1982).
7. W. Furey, B. C. Wang, A. H. Robbins, L. L. Clancy, and C. D. Stout, Structure Determination of Cd, Zn Metallothionein at 2.3 Å Resolution, ACA Meeting Abstract A #2, Stanford, CA, August, 1985.
8. J. Karle, Acta Crystallogr. Sect. A **40**, 366 (1984).
9. Science **229**, 370 (1985).

Crystallographic Databases and Molecular Biophysics

The Cambridge Structural Database and the Brookhaven Protein Data Bank are primary resources for molecular biochemists, pharmacologists, and medicinal chemists. The Brookhaven Protein Data Bank[1] contains atomic coordinates for 237 protein structures determined by x-ray crystallographic techniques. These data provide accurate information on the molecular architecture of the active sites of numerous enzymes and other proteins of physiological importance (see Fig. 1). Systematic analysis of the data have been used to elucidate basic patterns in tertiary structure of proteins. These patterns have been useful in tracing molecular evolution and in developing guidelines for predicting the three-dimensional structure of proteins on the basis of their amino acid sequence. The frequency with which different amino acid residues have been observed to occur in α-helical segments of proteins has long been one of the most reliable guides to predicting protein conformation. Recently a careful examination of the β turns in the protein structure in the data bank revealed a new correlation, an unexpected relationship between the twist of the hairpin turn and the twist of the β sheet formed by the turn.[2] Two distinct classes of β turns could be identified and a strong correlation between the identity of the amino acid residues at the turn and the type of β turn generated was detected.

The Cambridge Structural Database (CSD)[3] contains precise, accurate, and detailed information on the molecular structures of over 45,000 organic and organo-metallic compounds including drugs, natural products, and chemicals. Over 5000 new structures are added each year. Computer software developed at Cambridge, England allows the database to be searched by molecular name, connectivity, or bibliography. Fragment searches allow one to retrieve all structures having a specific fragment. The variation in molecular geometries of the fragment can be analyzed so that the effect of substitution upon its stereochemistry and atomic properties can be determined.[4] Through such analysis it has been possible to demonstrate that specific types of bond lengths and angles seldom deviate from characteristic values and that when they do the intramolecular source of variation can be readily identified. These types of data are useful guides to the development of empirical force field and molecular mechanics programs of ever increasing sophistication. These programs can in turn be used to predict the shape, stability, and properties of new candidates for synthesis and biological testing.

Recently, Murray-Rust and Raftery analyzed the Cartesian coordinates of 48 tripeptide fragments from the CSD to classify the molecules into groups and analyze the variation of geometry in the groups.[5] Through their analysis they were able to elaborate upon and refine a previously proposed classification scheme. The results of this type of analysis can

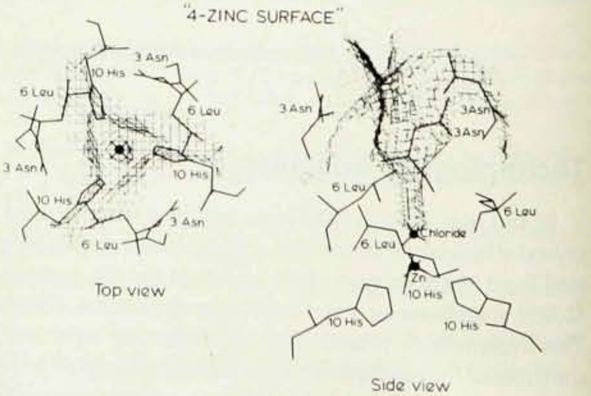

FIG. 1. Graphics analysis illustrates the inaccessibility of the Zn ion at the bottom of the narrow channel that accounts for the slow dissolving property of this therapeutically useful slow dissolving insulin [G. D. Smith *et al.*, Proc. Natl. Acad. Sci. U. S. A. **81**, 7093 (1984)].

be used to guide the synthesis of synthetic peptide hormones which would have desired overall shapes, to permit more reliable prediction of protein folding, and to predict the influence of amino acid variation on protein binding or active site characteristics.

William Duax

1. For further information contact Thomas Koetzle, Brookhaven National Laboratory, Building 555, Upton, NY 11973.
2. B. L. Sibanda and J. M. Thornton, Nature **316**, 170 (1985).
3. For further information contact W. L. Duax, Medical Foundation of Buffalo, 73 High Street, Buffalo, NY 14203.
4. F. H. Allen, O. Kennard, and R. Taylor, Acc. Chem. Res. **16**, 146 (1983).
5. P. Murray-Rust and J. Raftery, J. Mol. Graph. **3**, 50 (1985).

Molecular Structure and Engineering

Most biological processes are controlled by specific molecular interactions. In a great many cases the binding of a small molecule (drug or hormone) to a macromolecule (protein or nucleic acid) is a controlling factor in the process. In most cases the drug or hormone involved in the biological process has been isolated, purified, and identified and very often precise information on the three-dimensional structure is available from x-ray analysis. In favorable cases the protein target of the drug or hormone has also been purified and crystallized but more often than not the protein or nucleic acid target has not been isolated or fully characterized. The target proteins include transport and binding proteins, receptors, and enzymes that control specific metabolism or growth related processes.

If the crystal structure of the macromolecular target with the drug or hormone in the active site can be determined the molecular details of the interaction revealed can guide the synthesis of new drugs having specific properties. One can alter the strength and duration of the substrate–protein interactions by chemical modification of either the drug or the macromolecule.

Dihydrofolate reductase is an enzyme essential to the synthesis of DNA. Because the blockade of this enzyme results in cell death, inhibition of the enzyme is useful for cancer chemotherapy and the development of more potent and specific blockers of the enzyme is of great interest. The crystal structures of dihydrofolate reductase from four sources have been determined as complexes with enzyme cofactors and inhibitors. These results provide information concerning the backbone conformation, spatial arrangement of the residue side chains, and a description of the inhibitor binding site.[1]

The prominent role played by hydrogen bonding in the determination of stereospecificity was elegantly demonstrated in a study conducted by a group at the Imperial College of London[2] that involved protein engineering of tyrosyl-tRNA synthetase. By systematically altering the amino acids in the active site of the enzyme the strength and importance of the hydrogen bonds that determine the substrate specificity was clearly demonstrated. One of the remarkable and unexpected findings of this study was that a hydrogen bond involving a side chain with a net charge is stronger by a factor of 6 than a hydrogen bond to an uncharged side chain. Thus, the substrate affinity can be readily increased or decreased by altering the residues in the active site accordingly.

Evidence for the importance of hydrogen bonding in another class of proteins came from the x-ray analysis of a sulfate binding protein from Salmonella typhimurium.[3] This is one of a family of proteins which act as initial receptors for active transport systems.

Other milestones in structural elucidation of the past year include the x-ray structure determination of the first complex of a DNA repression protein with the DNA sequence that it recognizes, the first mammalian virus structure, and the structure of the octamer histone core of the nucleosome.

Regulatory proteins turn genes on and off by binding to specific DNA sequences. The crystal structures of a number of the uncomplexed regulatory proteins have been determined since 1981 and models for the binding of the protein to B-DNA were postulated and simulated using computer graphics. In 1984, John Rosenberg of the University of Pittsburgh School of Medicine reported the 3 Å resolution determination of the structure of a complex of the restriction enzyme EcoRI with its target DNA sequence.[4] Restriction enzymes bind to the DNA, just as the regulatory proteins do, but the enzymes cut the DNA instead of activating or repressing it. Anderson, Ptashne, and Harrison from Harvard have now reported the x-ray study of a complex of the repressor protein of coliphage 434 and the 14-base pair DNA sequence that the protein recognizes.[5] The structure determination reveals that the repressor interacts with the DNA just as the models had predicted and produces very little deformation of the B-DNA structure. In contrast, the restriction enzyme DNA complex revealed distortions in the helical structure that are likely to be correlated with the functioning of the enzyme.

Making extensive use of the most recent technological advances, Michael Rossman and co-workers at Purdue University in Indiana and the University of Wisconsin have determined the structure of the human cold virus HrV14.[6] The 800,000 intensity data needed for the study were collected using the Cornell University High Energy Synchrotron Source and the structure determination and refinement were completed using a Cyber 205 supercomputer. The structure was found to be strikingly similar to known icosahedral plant RNA viruses. Immunogenic regions on the virus identified by biochemical studies conducted by Roland Ruckert at the University of Wisconsin were observed to reside on external protrusions of the icosohedron, a large cleft on each face is proposed as the host cell receptor binding site. Armed with detailed knowledge of the surface geometry new kinds of antiviral drugs may be designed to treat colds.

The crystallographic structure determination of a second mammalian virus, the polio virus was reported by a group from the Research Institute of the Scripps Clinic.[7] Describing the significance of these x-ray determinations of virus structures David Baltimore of the Whitehead Institute in Cambridge, Massachusetts said: "(These) beautiful pictures will forevermore be the basis of thinking about how viruses are assembled, how they are held together, and how they are taken apart to infect cells."[8]

The nucleosome is the primary repeating unit of DNA organization in chromatin. The nucleosome core is a well defined particle composed of 146 base pairs and an octamer of histone proteins. A group from the MRC laboratory in Cambridge, England reported the determination of the crystal structure of the core particle at 7 Å resolution late in 1984.[9] Subsequently, a research team at Johns Hopkins University in Baltimore reported the structure of the histone core of the nucleosome at 3.3 Å resolution.[10] The fact that the structures of the histone cores reported by the two authors differ in size, shape, and internal arrangement has generated a heated debate that will only be laid to rest with further refinement at higher resolution of these and related structures.

William Duax

1. B. Mathews, J. Biol. Chem. **260**, 392 (1985).
2. A. R. Fersht, J.-P. Shi, J. Knill-Jones, D. M. Lowe, A. J. Wilkerson, D. M. Blow, P. Brick, P. Carter, M. U. Y. Waye, and G. Winter, Nature **314**, 235 (1985).
3. J. W. Pflugrath and F. A. Quiocho, Nature **314**, 257 (1985).
4. C. A. Frederick *et al.*, Nature **309**, 327 (1984).
5. J. E. Anderson, M. Ptashne, and S. C. Harrison, Nature **316**, 596 (1985).
6. J. P. Griffith *et al.*, Nature **317**, 145 (1985).
7. J. M. Hoyle, M. Chow, and D. J. Filman, Science **229**, 1358 (1985).
8. D. Baltimore, Science **229**, 1366 (1985).
9. T. J. Richmond, J. T. Finch, B. Rushton, D. Rhodes, and A. Klug, Nature **311**, 532 (1984).
10. R. W. Burlingame *et al.*, Science **228**, 546 (1985).

PHYSICS EDUCATION

Developments in physics education in 1985 covered the entire educational spectrum from elementary school to graduate school. Private organizations, national laboratories, and industry led the way with a multitude of new programs and activities. At the National Science Foundation it was a year of reorganization and reactivation as new programs were put into place in precollege education and a very small undergraduate program was developed. Funding at the National Science Foundation was cut significantly, but the cut was distributed across two years by carrying funds forward from FY1985 to FY1986. The head of Science Education at NSF, Dr. Bassam Shakhashiri, also redirected existing funding by increasing NSF support for activities in elementary and middle school science.[1] At the same time, Roland Schmitt, the Chairman of the National Science Board, appointed a committee, chaired by Homer Neal of Stony Brook, to study the state of undergraduate science and engineering education and to make recommendations for NSF actions. Schmitt observed that although "NSF and other agencies now have programs at both the graduate and precollege levels...no systematic Federal leadership or support exists for science, engineering, and mathematics education at the undergraduate level." Such support had been called for at the Conference of Physics Department Chairs held in the spring of 1985, and Schmitt had been present at the conference as an invited speaker.

The scientific societies were putting into place their own efforts in support of education at all levels. The American Association of Physics Teachers (AAPT) launched its Physics Teaching Resource Agent program with support from NSF.[2] The American Physical Society (APS) surveyed the "Quality and Quantity of Undergraduate Physics Majors" with support from AIP and AAPT.[3] The American Association for the Advancement of Science developed the "National Forum for School Science" in conjunction with the Carnegie Corporation of New York.[4] The National Academy of Sciences/National Research Council studied and developed a report on the "Indicators of PreCollege Education in Science and Mathematics" that concluded that the data gathering efforts in this area must be increased.[5]

AAPT and APS together sponsored a conference[3] of physics department chairs on "Education for Professional Work in Physics." The Triangle Coalition of Business, Science, and Education pulled together most of the major scientific and science education organizations to work together on common activities in support of precollege education in science.[6] AIP and AAPS are members of the coalitions and APS, the Optical Society, and several other AIP member societies have been active in some of the programs. The Triangle coalition sponsored a number of activities for the National Science Week in May 1985 including a nationwide balloon launch reported on the network news.

The Optical Society formed an education committee to study the present educational situation and how topics in optics might be used in high school courses. They also sponsored a seminar for teachers at the AAPT summer meeting and developed a special program for local high school teachers in conjunction with their October meeting.

The level of activity demonstrated by the scientific societies is without precedent and is clearly making an important impact on the very large problems facing science education in the United States. These efforts have been aided by the efforts of industry, the national laboratories and the private foundations. "The Mechanical Universe," a college physics course developed at the California Institute of Technology with the support of the Annenberg/CPB project became available for use in 1985, and, with support from NSF, a high school version was produced as well. Use of videodisk technology became more prevalent as several projects came to conclusion while others were initiated with the support of various foundations.

The international character of physics education was reemphasized through the development of many joint activities detailed below, and international cooperation is expected to increase in the coming year in spite of the withdrawal from UNESCO of the United States.

Jack M. Wilson, University of Maryland

1. J. Wilson, AAPT Announcer **15**, 72 (May 1985).
2. AAPT Announcer **15**, 43 (September 1985).
3. R. Resnick, in *Proceedings of the Conference on Education for Professional Work in Physics*, edited by D. Holcomb and J. Wilson (AAPT, College Park, MD, 1985).
4. Science.
5. *Indicators of Precollege Education in Science and Mathematics* (National Academy, Washington, DC, 1985).
6. Phys. Today **38**, 80 (May 1985).

Survey of Physics Programs on the Quality and Quantity of Physics Majors

A survey of the chairpersons of all U. S. physics departments was designed to get opinions and new ideas on how to raise the quantity and quality of undergraduate physics majors. It was conducted by The American Physical Society with assistance from AIP and AAPT. The number and quality of physics majors is affected by a whole range of issues, from the crisis in science and math instruction in the primary and secondary schools to the national economy and the job market for physicists. The survey focused on the short term and dealt with the current situation. Apart from calling for new ideas and general comments, the survey asked for specific ratings and comments on a list of curriculum offerings, educational materials, and physical resources for undergraduates, programs to attract women and minority students into physics, visiting scientist programs and undergraduate research participation programs.

Responses were received from 553 of the 791 physics departments, a 70% rate. A detailed summary of the ratings and comments on the ten specific items to be evaluated is given in the Proceedings of the Conference of Physics Department Chairs from the American Association of Physics Teachers. The areas of highest priority were the need for laboratory equipment, the establishment of undergraduate research programs, and computer access.

The survey committee developed some general conclusions from the results and analysis of the comments section as to how physics departments could raise the quality and quantity of undergraduate physics majors:

(1) Greatly increase the interaction between physics faculty and high school math and science students and teachers.

(2) Put your best people into the introductory physics courses as lecturers and recitation–discussion leaders, for if you cannot win students over in that course then all the subsequent programs and ideas that are suggested are much less effective. In that introductory course the area of most concern, however, is in the laboratory—the low quality of the experiments, the equipment or the teaching assistants.

(3) Involve students in undergraduate research participation programs early on, for access to research laboratories attracts undergraduates. The single item that was regarded as the most effective way to get high caliber undergraduate students into physics and to keep them there was involvement in research.

(4) A significant number of students who like physics choose, nevertheless, to major in engineering or computer science, according to comments received, because a physics bachelor's degree is viewed as less saleable than one in engineering or computer science. Here the advice was to educate recruiters and industry in general on the value and virtues of an undergraduate physics program and to correct high school counselors' false impression that the physics job market is still poor.

(5) Moreover, curriculum offerings should be expanded in applied areas of physics and more use made of joint majors, especially with engineering and computer science departments.

(6) To raise or maintain the quality of the undergraduate physics majors program, especially at the small schools, respondents called for expanded funding for undergraduate research participation programs, for purchase of modern equipment in the upper-division laboratories, and to sponsor visiting scientist programs.

(7) And, finally, we should greatly increase the opportunities, use, and visibility of women and minorities already in physics as role models to attract more majors from these ranks.

Robert Resnick, Rensselaer Polytechnic Institute

Physics Teacher Resource Agents Program

The Physics Teacher Resource Agents are 104 outstanding physics teachers trained by the American Association of Physics Teachers (AAPT) with support from a grant of $477,000 from the National Science Foundation.[1] The project, under the direction of Don Kirwan of the University of Rhode Island and Jack Wilson of AAPT and the University of Maryland is the largest national program designed to effect a rapid improvement in the state of high school physics teaching by training outstanding teachers to work with other teachers in their areas.

The Physics Teacher Resource Agents (PTRA) were selected from more than 900 applicants nationwide, and attended a workshop at Northern Arizona University in Flagstaff from 10–28 June to train them to run workshops for other physics teachers. Areas of training included: lecture demonstrations, computers in physics, laboratory techniques, media (production of slides, transparencies, films, and video materials), and workshop organization and leadership. The teachers were also given briefings on current research in physics and physics education through interactions with prominent research scientists.

The 104 Physics Teacher Resource Agents should be able to reach over a thousand other physics teachers in the first year along through workshops now being organized throughout the country for those teachers unable to attend the original training program. This represents a significant fraction of the physics teachers presently teaching. Given the critical shortage of physics teachers and the large number of individuals teaching physics who were trained in other teaching fields, the Resource Agents program is expected to have an immediate and important beneficial impact on the state of physics teaching in the United States. The program will continue with additional training for the existing Resource Agents and selection and training of more PTRA.

D. Kirwan, University of Rhode Island

1. Physics Today **38**, 72 (June 1985).

Education of the Physicist for Professional Work in Physics

Although physics research has flourished during the last decade, serious educational and manpower problems lie ahead. Representatives of some 150 physics departments in U. S. colleges and universities heard warnings of trouble ahead and debated ways to forestall it at the second Conference of Department Chairs in Physics, held on May 17–18, 1985 under the auspices of the American Association of Physics Teachers and The American Physical Society.[1] The theme of the meeting was "Education for Professional Work in Physics."

One of the talks considered the study of national science policy being carried out by the House Committee on Science and Technology. With a 1986 report date, the study will consider a broad range of issues affecting the Federal government's support of basic and applied research in physics and other sciences and engineering. A central question is whether the traditional mechanisms for allocating support to science will continue to serve the nation well in an era of intense international economic competition, budget deficits, multidisciplinary research projects, and large-scale research enterprises competing with "small science."[2]

Assessing manpower issues, Dale Corson, president-emeritus of Cornell, described a number of serious problems that have intensified in recent years. These include: depressed annual production of physics Ph.D.s, a decline in the percentage and numbers of U. S. citizens receiving a physics Ph.D., little progress in recruitment of minorities and women, a median age of physics faculties that is the highest of any of the sciences or engineering (and rising rapidly), and demographic trends likely to reduce the number of physics graduates until well into the 1990's. Smaller physics departments, in particular, are likely to find the next few years quite difficult.

D. F. Holcomb, Cornell University,
W. C. Kelly, AAPT, and J. M. Wilson

1. Phys. Today **38**, 70 (July 1985).
2. Daniel Kleppner, Phys. Today **38**, 78 (March 1985).

ELECTRON AND ATOMIC PHYSICS

Electron Cyclotron Resonance Ion Sources

The use of Electron Cyclotron Resonance (ECR) ion sources in atomic physics experiments has opened the door to many new areas of multicharged ion collision physics research. An ECR ion source, in which ions are formed in a hot plasma undergoing a cycle of compression and expansion, has been used to study electron capture by bare nuclei of such atoms as C, N, O, F, and Ne during collisions with atomic hydrogen at relative velocities slow compared to the orbital velocity of the bound electron.[1] At these velocities a short-lived, one-electron diatomic "quasimolecule" is formed during the collision. Owing to their simplicity, these true three-body systems have been extensively studied by theorists, although experimental investigations have only recently been possible.[2] The measurements provided important benchmark data against which previously untested theoretical calculations could be compared.

The same ion source was also used in a study of electron-impact ionization of Mg-like multicharged ions.[3] The electron collision experiment provided valuable information on the increasing relative importance of indirect mechanisms such as excitation–autoionization in the collisional ionization of multicharged ions by electrons as the ionic charge increases along an isoelectronic sequence (i.e., fixed electronic configuration). The collisional behavior of multicharged ions plays a significant role in fusion plasma modeling calculations of impurity transport and recycling, in the study of ionization balance of magnetically confined fusion plasmas, and in the interpretation of plasma diagnostics.

David Golden, North Texas State University

1. F. W. Meyer, A. M. Howald, C. C. Havener, and R. A. Phaneuf, Phys. Rev. Lett. (to be published).
2. D. Dijkkamp, D. Ciric, and F. J. Heer, Phys. Rev. Lett. **54**, 1004 (1985).
3. A. M. Howald, D. C. Gregory, F. W. Meyer, R. A. Phaneuf, A. Muller, N. Djuric, and G. Dunn, Phys. Rev. (submitted).

The Transverse Doppler Effect

Einstein's special theory of relativity was obtained deductively from two postulates: the constancy of the speed of light, and the principle of special relativity (which states that the laws of physics are the same in uniformly moving coordinate frames). These postulates lead to the Lorentz transformation from which a number of kinematic results for particles in relative uniform motion may be predicted and compared to experiments. One of these predictions is that a moving clock runs slower, and that its frequency is thereby reduced. This relativistic effect is also known as the transverse Doppler effect, since it gives a red shift proportional to v^2/c^2 even if there is no first order Doppler shift.

The relativistic Doppler effect may be measured experimentally by spectroscopic techniques. If moving atoms are used as "clocks," then their transition frequencies measured by an observer in the laboratory should show the relativistic corrections.

A team of scientists has measured the relativistic Doppler effect in neon atoms to an accuracy of one part in 25 000.[1] By using two-photon spectroscopy—in which an atom makes a transition by simultaneously absorbing two laser photons with the same frequency but traveling in opposite directions—the first order Doppler effect is eliminated owing to the exact cancellation of the large individual shifts of each photon. The relativistic Doppler effect is obtained by measuring the frequency difference between a two-photon transition of neon atoms in a fast moving beam and in a stationary cell. Two continuous-wave dye lasers are used, one stabilized to the fast beam transition and the other to the cell transition. The beat frequency between the two lasers is then measured directly.

One promising feature of the experiment is the use of resonant two-photon spectroscopy with the moving clocks. In this method the fast atomic beam and the laser beams are collinear. It is then possible to Doppler tune a particular intermediate level of the two-photon transition into exact resonance with the laser. In essence the velocity of the fast atoms is no longer arbitrary but is dictated by the resonance condition. The advantage is that this velocity may be calculated from the known energy levels of the atom. Thus a major source of error, that due to the determination of the beam velocities, is eliminated. The experiment is in excellent agreement with the predictions of special relativity and provides the most accurate verification of the time dilation effect to date. The authors foresee a further improvement by a factor of 1000 when the experiment is carried out in a storage ring.

David Golden

1. M. Kaivola, O. Poulsen, R. Riis, and S. A. Lee, Phys. Rev. Lett. **54**, 255 (1985).

Looking for Time-Reversal Asymmetry in Atoms

Recent atomic physics experiments have placed improved limits on violations of the fundamental symmetry principles of local Lorentz invariance and time-reversal invariance. These experiments make use of the remarkable frequency resolution available with new spectroscopic techniques.

General relativity and other metric theories of gravitation are based on the Einstein equivalence principle, which states that (1) all test bodies fall with the same acceleration, (2) the outcome of any nongravitational experiment in a local freely falling frame is independent of where and when it is performed, and (3) the outcome of any nongravitational experiment in a local freely falling frame is independent of the velocity and orientation of the frame (local Lorentz invariance).[1] Local Lorentz invariance is tested most precisely by experiments which attempt to measure the dependence of energy-level spacings in an atomic system on the orientation of the system relative to some preferred direction in space.

In recent experiments, the frequency of a 303 MHz hyperfine structure transition in $^9Be^+$ ions was compared to that of a passive hydrogen maser and was found to vary by not more than 100 μHz over a sidereal day as the rotation of the earth changed the orientation of the ions (fixed by the laboratory magnetic field) with respect to the external universe.[2] The ions were confined by static magnetic and electric fields under ultrahigh vacuum conditions. Laser radiation, tuned to a frequency slightly below an optical resonance, cooled the ions to below 1 K. This cooling process, which was crucial to the experiment because it reduced the relativistic time dilation frequency shift, depends on the fact that the laser radiation pressure force is greater for ions moving against the beam than for ions moving with the beam owing to the Doppler effect. Transitions between hyperfine states, driven by a radio frequency field, were detected by observing a change in the fluorescence intensity. The hyperfine resonance linewidth was 0.025 Hz, and the signal-to-noise ratio was sufficient to locate the center to about 100 μHz in a two hour run. These results improve on those of the previous experimental measurement by about a factor of 300.

Observation of a permanent electric dipole movement (EDM) in an atomic system would indicate a violation of time-reversal (T) symmetry, which until now has been observed only in the K_0 meson system.[3] Such an EDM might be attributed to an intrinsic EDM of the electron or of the particles inside the atomic nucleus, or to T violation by any of the forces between the particles making up the atom. These results set a new lower limit on the size of a T-violating, short-range electron–nucleon interaction, and for certain models of T-violating quark–quark interactions, provide limits comparable to those obtained from the neutron EDM measurement.[4]

David Golden

1. C. M. Will, *Theory and Experiment in Gravitational Physics* (Cambridge University, Cambridge, 1981).
2. J. D. Prestage, J. J. Bollinger, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. **54**, 2387 (1985).
3. J. H. Christenson, J. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
4. V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, JETP **87**, 1521 (1984).

Inhibiting Spontaneous Emission

Spontaneous emission, the process by which an atom in an excited quantum state deexcites by the mission of a photon, has been considered by physicists to be based on an inviolate law of nature. All excited states must eventually decay. In the language of quantum mechanics, the ground state is the only stationary state of a system. Recently, it has been demonstrated that spontaneous emission by excited atoms can be suppressed by the presence of the conducting walls of an electromagnetic cavity.[1]

Recently researchers have performed experiments which establish that the rate of spontaneous emission can be strikingly different in a cavity than in free space.[2-4] In one experiment[1] a thermal beam of cesium atoms were prepared in a "circular" state characterized by a high level of excitation and angular momentum, which in the classical picture corresponds to an electron in a large circular orbit about the atomic nucleus. Atoms in circular states are ideally suited for studying spontaneous emission because: (1) they can decay via only one channel and (2) the wavelength of the decay photon is long (about 0.5 mm), permitting the use of macroscopic cavities for the experiments. The circular state is created using a pulsed dye laser/microwave scheme.[5] The atom must absorb approximately 20 photons to achieve the high angular momentum circular orbit. Once the atoms in the beam have been excited to the circular state they drift into the cavity, which consists of two parallel, gold-plated aluminum plates. The plate separation is determined by precise quartz spacers to be very nearly equal to one-half of the decay photon wavelength. When one-half wavelength is greater than the plate separation there are no modes of the vacuum for the photon to decay into, so the atom must remain excited.

This situation is similar to a waveguide which cannot support radiation of a wavelength larger than the cutoff wavelength. The decay rate is determined by counting the atoms emerging from the cavity which have remained in the initially prepared state. By electronically tuning the transition wavelength about the cutoff by use of the Stark effect, the spontaneous decay may be switched on or off, providing a spectacular demonstration that indeed the "vacuum" is not empty. The experimental results may be quantitatively compared to theory because the mode structure of the parallel plate cavity is straightforward to calculate (circular states have only one decay channel). The researchers are able to place a lower limit of a factor of 8 on the increase of the excited state lifetime in the cavity relative to that for free space.

In view of the fact that spontaneous emission is the ultimate source of quantum noise, there may be intriguing applications for inhibiting spontaneous emission. For example, it may be possible to get around the limitation on the precision of certain measurements imposed by the Heisenberg uncertainty principle.

David Golden

1. R. G. Hulet, E. Hilfer, and D. Kleppner, Phys. Rev. Lett. (submitted).
2. P. Goy, J. M. Raimond, M. Gross, and S. Haroche, Phys. Rev. Lett. **50**, 1903 (1983).
3. D. Meschede, H. Walther, and G. Muller, Phys. Rev. Lett. **54**, 551 (1985).
4. G. Gabrielse and H. Dehmelt, Phys. Rev. Lett. (submitted).
5. R. G. Hulet and D. Kleppner, Phys. Rev. Lett. **51**, 1430 (1983).

Trapping Neutral Atoms

Laser-cooled, trapped ions have been successfully used for a number of years,[1,2] as have trapped electrons[3] and neutrons.[4] Until recently, however, the prospect of electromagnetic confinement without material walls has not been realized for neutral atoms. This has been true in large part because the electromagnetic forces which can be applied to neutral atoms are quite small, so that only very slow atoms (with equivalent temperatures of less than about 1 K) can be held by such forces. Recently, two groups[5,6] have used laser cooling to produce stopped atoms with a low enough energy spread to be trapped.

The basic technique is to oppose an atomic sodium beam with a laser beam tuned to resonance with an atomic transition frequency.[7] The strong radiation pressure force slows and eventually stops the atoms. Ordinarily, however, the changing Doppler shift of the decelerating atoms would quickly shift the atoms out of resonance with the laser before the atoms could be stopped. One way to overcome this difficulty is to use a changing magnetic field to compensate the changing Doppler shift. Another technique is to frequency shift the laser. Both techniques have produced samples of sodium atoms with a velocity distribution centered at zero and having a spread of only a few meters per second. This corresponds to temperatures of tens of millikelvins.

The production of such a cold, stopped atom sample has enabled electromagnetic trapping of neutral atoms.[8] The trapping potential is provided by the energy of interaction between the magnetic moment of the sodium atoms and the inhomogeneous field of the quadrupole trap. The trap is loaded by first bringing the atomic beam to rest in the varying magnetic field provided by just one of the trap coils. Then the opposing coil is turned on, completing the trapping field. Atoms as fast as 3.5 m/s (17 K equivalent temperature) can be contained by the trap. However, only those atoms in quantum states whose energy increases with increasing magnetic field can be confined in a magnetic trap.

These new advances in laser cooling and the first demonstration of neutral atom trapping suggest a number of new opportunities. We can expect to see true optical traps, extreme cooling to microkelvin temperatures, high densities of trapped atoms and applications to spectroscopy, collisions, lifetime measurements, and quantum collective effects.

David Golden

1. D. Wineland *et al.*, Phys. Rev. Lett. **40**, 1639 (1978).
2. W. Neuheuser *et al.*, Phys. Rev. Lett. **41**, 233 (1978).
3. P. Ekstrom and D. Wineland, Sci. Am. **243**, 104 (February 1980).
4. K. J. Kugler, W. Paul, and U. Trinks, Phys. Lett. B **72**, 422 (1978).
5. J. V. Prodan *et al.*, Phys. Rev. Lett. **54**, 992 (1985).
6. W. Ertmer *et al.*, Phys. Rev. Lett. **54**, 996 (1985).
7. Phys. Today **38**, 17 (June 1985).
8. A. Migdall *et al.*, Phys. Rev. Lett. **54**, 2596 (1985).

High Resolution Laser Spectroscopy

A significant advance in the high resolution laser spectroscopy of the simple hydrogen atom has been made this year.[1] This advance will allow more accurate determination of the values of fundamental constants as well as a stringent test of quantum electrodynamics (QED), the theory that describes the electromagnetic force, as it pertains to this elementary, two-body system. In this experiment the transition from the ground state ($1S_{1/2}$) to the first excited metastable state ($2S_{1/2}$) was observed with a resolution of five parts per billion. Improvements to the apparatus, now being made, will enable this resolution to be improved by at least another factor of 1000.

In the recent experiment the 1s–2s transition was excited by two-photon Doppler-free spectroscopy using a continuous wave (cw) source of ultraviolet radiation with a wavelength of 243 nm. This is the first time this transition has been seen with a cw source. The ultraviolet radiation was generated by sum-frequency mixing the output of two lasers in a crystal of potassium dihydrogen phosphate, because at present there are no tunable lasers which operate at this wavelength. To obtain enough ultraviolet power the beam from one of the lasers was enhanced by a resonant optical cavity placed around the crystal and there was another enhancement cavity about the interaction region. Although the bandwidth of the cw source can be greatly reduced, it was not this bandwidth which limited the resolution in the recent experiment but rather the finite interaction time of the atoms as they moved through the beam; the interaction region was filled with atomic hydrogen at low pressure and room temperature so collisions also contributed to the linewidth. Both of these effects will be reduced in an atomic beam which has been cooled to liquid helium temperature and in which the atoms travel along the light waves. In the future atoms could be cooled still further to millikelvin temperatures by radiation pressure or by magnetic fields. Not until the atoms are almost stationary does the resonance width approach the natural width. One way to achieve this would be to direct very cold atoms upwards so that they are slowed by gravity, in a "hydrogen fountain," and then observing them near the turning point. These ideas show how resolution can continue to be increased by orders of magnitude and demonstrate that the spectroscopy of even the first atom in the periodic table is far from finished.

David Golden

1. C. J. Foot, B. Couillaud, R. G. Beausoleil, and T. W. Hansch, Phys. Rev. Lett. **54**, 1913 (1985).

ELEMENTARY PARTICLE PHYSICS

Superstrings

One of the chief goals of theoretical particle physics is the development of a theory that can account for the four forces of nature: gravity, electromagnetism, and the strong and weak nuclear forces. So far there has been partial success. Steven Weinberg, Sheldon Glashow, and Abdus Salam won a Nobel Prize for their electroweak theory which fits the electromagnetic and weak forces together in a single framework. Other scientists are trying to integrate the electroweak and strong forces into a "grand unified theory." This theory would not actually be "grand" since it would not assimilate gravity. "Supergravity" is a theory, still in a formative stage, that *does* address the problem of gravity; it calls for the existence of a whole new family of particles, some of which are being sought at the European laboratory CERN and elsewhere.

There is now a new, potentially all-inclusive, unified theory. Michael Green, of the University of London and John Schwarz of Caltech have outlined the "superstring" theory,[1] the principal features of which are these: the dimensions of the universe consist of the usual 4 (3 for space and 1 for time) plus 6 more (which cannot be observed since they are infinitesimally curled up) for a total of 10; elementary particles such as quarks, leptons, and gauge bosons are regarded not as point-like but as tiny, one-dimensional strings about 10^{-35} m long; all four forces are united in a single framework that is reconciled with quantum mechanics (previous theories have not succeeded in bringing gravity and quantum mechanics together); the property (known as "chirality") that the laws of physics are not symmetrical under reflection in a mirror is preserved; the theory appears to have no "infinities" (nonsensical terms appearing in the calculation of interaction probabilities) or free parameters (factors that can be adjusted to make the theory fit the experimental evidence); the theory calls for the existence of a new class of matter, called "shadow matter," which only interacts gravitationally.[2] Some astronomers associate shadow matter with "dark matter," the nonluminous stuff that seems to lurk in or around many galaxies.

Many theorists seem excited by the superstring theory.[3] It might at last be a theory that unifies the four forces of nature without incurring the kind of difficulties that have plagued supergravity so far. It may be difficult, however, to validate the model experimentally, so acceptance of the theory will take some time. Several versions of the theory have now appeared.[4,5]

Phillip F. Schewe, American Institute of Physics

1. M. Green and J. Schwarz, Phys. Lett. B **149**, 117 (1984); **151**, 21 (1985).
2. M. Green, New Scientist **107**, 35 (29 August 1985).
3. B. M. Schwarzschild, Phys. Today **38**, 17 (July 1985).
4. D. J. Gross, J. A. Harvey, E. Martinec, and R. Rohm, Phys. Rev. Lett. **54**, 502 (1985).
5. P. Candelas, G. T. Horowitz, A. Strominger, and E. Witten, Nucl. Phys. B (to be published).

The Continuing Search for Proton Decay

The theories that seek to combine in one mathematical framework a description of the strong, weak, and electromagnetic forces, the grand unified theories (GUT), predict that the basic building blocks of nuclei, protons, and neutrons are unstable, with measurable lifetimes, according to one version of the theory, of about 5×10^{29} years. These predictions were subsequently shown experimentally to be too optimistic by nearly a factor of 1000.[1]

Nonetheless, the idea that protons will decay persists. Theoretically it is attractive. For example, it gives rationale to the many similarities between quarks and leptons and it explains the absence of a long-range force between baryons (that is, a force sensitive to baryon number). There may even be some indirect experimental evidence for it: the baryon/antibaryon asymmetry in the universe to which we owe our very existence can be attributed to a fundamental baryon nonconservation law operating at the time of the big bang. In 1964 Steven Weinberg explained[2] that "the apparent baryon and lepton non-neutrality of the universe...leads us to the strong suspicion that baryon number and lepton number are not precisely conserved."

These weighty matters have spurred the development of several large dedicated proton decay detectors over the past six years. Experiments are now operating in several deep underground locations around the world: the Kolar Gold Fields in India, the Mont Blanc and the Frejus tunnels in Europe, a heavy metals mine 300 km west of Tokyo, and a salt mine east of Cleveland.[3] A new experiment is being constructed in an iron mine near Duluth and other new detectors are being contemplated in India, Japan, and Italy. Since the early pioneering efforts,[4] there has been considerable progress made recently on the question of matter stability. Lifetime limits on dozens of possible proton decay modes have been set by the various experiments.[5] Limits for decay modes not involving neutrinos are in the range 5×10^{31} to 5×10^{32} years. Neutrino modes are more severely affected by atmospheric neutrino-induced background events and consequently have limits typically in the range of 10^{30} years.

In the meantime some modest theoretical progress has been made. Predictions made using SU(5), the name for the earliest version of GUT, have been revised. Furthermore, supersymmetry, another unified gauge theory, predicts that decay modes involving the K meson might be detectable by present experiments. An even newer theory, the superstring model, will undoubtedly accommodate the present experimental constraints on proton decay.

What is the future of the subject? It seems clear that several more years of effort are needed on the experimental side. Better understanding of the neutrino-induced background is needed in order to allow progress on background-limited decay modes. Candidate events, consistent with one or more decay modes, are being found at a level of a few percent of the neutrino background rate. Will a consistent picture develop in which a few dominant proton and neutron decay modes can be definitively ascertained? Only time will tell.

Experimenters are regrouping to attack the question with new and improved detectors at Frejus, in Japan (Kamioka), at the Kolar Gold Fields, in Cleveland (IMB), and in Minnesota (Soudan 2). Clearly the subject is alive and well; but the question still remains: is the proton?

J. C. van der Velde, University of Michigan

1. H. S. Park, G. Blewitt *et al.*, The IMB Collaboration, Phys. Rev. Lett. **54**, 22 (1985).
2. S. Weinberg, Brandeis Summer School (1984), p. 482.
3. J. M. LoSecco, F. Reines, and D. Sinclair, Sci. Am. **252**, 54 (June 1985).
4. F. Reines, C. L. Cowan, and M. Goldhaber, Phys. Rev. **96**, 1157 (1954).
5. See reviews by M. Koshiba, Proceedings of the XXII International Conference on High Energy Physics, Leipzig (1984); D. Perkins, Proceedings of SWOGU 1985 (University of Minnesota, to be published); F. Vannucci, Proceedings of the International Europhysics Conference, Bari, Italy (1985).

CERN Collider Physics

The CERN $Sp\bar{p}S$ Collider, located near Geneva, Switzerland, is a storage ring for intense beams of protons and antiprotons. The beams are brought into collision in two experimental regions at a center-of-mass energy of 630 GeV (although the collider has been operated up to 900 GeV in a special ramped mode). It is possible that historians of science will someday regard the Collider as the machine of the Standard Model. The Standard Model is the name of the remarkably complete description of elementary particle physics that has been developed during the last 20 years. All strongly interacting particles, including the protons and antiprotons which circulate in the Collider, are seen to be bound states of quarks and gluons. Since quarks participate in both strong and electroweak interactions, the collider is an ideal place to test the two pillars of the Standard Model, Quantum Chromodynamics (QCD), and the Weinberg–Salam–Glashow theory of electroweak interactions.

Quantum Chromodynamics is the gauge theory that is thought to describe all strong interaction physics. The strong force is mediated by a family of eight spin-1 gauge particles called gluons. An important feature of the theory is the rather counterintuitive way in which the strong force varies with the distance between strong charges. At large distances (say, comparable to the nucleon dimension, about 10^{-13} cm), the strength of the interaction is large and the constituents of the proton are thus tightly bound. However, at the small distances that correspond to hard collisions (typically 10^{-16} cm at the Collider), the interaction becomes much weaker.

This property, known as asymptotic freedom, enables one to consider the collision of two hadrons in terms of the collisions of quasifree quarks and gluons. In very energetic proton–antiproton collisions, it is expected that occasionally a quark or gluon in one particle will violently scatter from a quark or gluon in the other particle. As the scattered constituents separate in space, the increasing strength of the strong force will cause them to "drag" other quarks and gluons along in the same directions. The observer should therefore see two collimated "jets" of particles emerging in opposite directions from the collision. Since the jets are the products of a hard scattering, they are often quite energetic and emerge with large angles with respect to the incident hadron directions. In other words, they have large transverse momenta with respect to the beam axis.

In 1982 as the first data from the Collider beam became available, the UA2 collaboration (consisting of more than 50 physicists) observed that the two-jet topology was indeed the dominant feature of large transverse momentum $p\bar{p}$ collisions.[1] Since that time both the UA2 group and their neighbors in the Collider's other intersection region, the UA1 collaboration, have found the features of two-jet production to be in accord with the predictions of QCD.[2] It has even been possible to use the two-jet data and QCD to extract information about the proton substructure (especially about the gluon content of the proton).[3]

A quark or gluon that is participating in a scattering process can occasionally emit an energetic gluon via the QCD bremsstrahlung process. In such events a third jet can be observed if the gluon is emitted at a large enough angle with respect to the radiating particle. This process is entirely analogous to the well-known QED bremsstrahlung of a photon which occurs with a probability that is proportional to the fine structure constant α. It is not surprising, then, that the QCD process occurs with a probability that is proportional to the analog of the fine structure constant, the strong coupling constant α_s. One can therefore measure α_s by comparing the observed number of three-jet events to the number of two-jet events. Both UA1 and UA2 have performed such analyses in 1985 and both find that a value of α_s near 0.2 best describes their data.[4]

The Collider is certainly best known for its contributions to the Weinberg–Salam–Glashow theory of electroweak interactions. The theory describes weak interactions in terms of the exchange of the gauge particles W^+, W^-, and Z^0. It was expected that the $W^\pm$ and Z^0 particles should be produced from the annihilation of quarks and antiquarks in the colliding hadrons. The W is most easily detected via its decay into a charged lepton (an electron or muon) and a neutrino (which is detected by an imbalance of transverse momentum in the detector). The Z^0 has an even more distinct signature, a very large-mass pair of charged leptons. In 1983 both kinds of gauge boson were discovered by both UA1 and UA2 groups.[5,6] At the current time the two groups have observed several hundred leptonic decays of the W and several tens of leptonic Z^0 decays. An important parameter of the electroweak theory is the expression $\sin^2\theta_w$ (θ_w is the weak mixing angle), which is closely related to the gauge boson masses. The current best measurement[7] of the UA2 group is $\sin^2\theta_w = 0.226$ (with a statistical error of ± 0.005 and a systematic error of ± 0.008), in good agreement with measurements from lower energy neutrino experiment.

In 1984 the UA1 collaboration published[8] evidence for the existence of the sixth quark, the top quark (see *Physics News in 1984*, p. 31). They observed six events containing a lepton and two hadronic jets. The events were interpreted as decays of the W into top–bottom quark pairs followed by the decay of the top quark into the charged lepton, a bottom quark, and a neutrino. The bottom quarks cannot be observed directly because of the strong QCD forces, but "materialize" as hadronic jets instead. As of the 1985 conference season, UA1 was reporting nine events with an electron and two jets (the muon data were not yet available). More detailed calculations indicated that only two to three events were expected from W decay but that the remainder could be due to the production of top–antitop quark pairs via the strong interaction. In the latter case one top quark would decay into an electron, a jet, and a neutrino and the other into a purely hadronic jet. It seems that final clarification of the "top picture" must await more work and perhaps more data.

While most of the observations made at the Collider have been in striking agreement with the predictions of the Standard Model, there have been several hints of more exotic phenomena (see *Physics News in 1984*, p. 34). In 1983 the UA1 and UA2 groups observed events in which the Z^0 boson decayed into a pair of charged leptons and an energetic photon.[6] In addition the UA2 group observed several events containing W bosons produced in association with large transverse momentum jets.[9] In both cases, probability for producing such events via ordinary processes was small (several percent) but not sufficiently small to rule out a Standard Model interpretation. At this writing the sizes of the respective data samples have been increased by roughly a factor of 3 and no more unusual events have been observed. In 1984 the UA1 collaboration published the observation of five events, each containing a single, unbalanced large transverse momentum jet.[10] At the time it appeared that no single Standard Model process could account for the observation. It now seems that the signal could be consistent with a combination of several Standard Model processes. As of this writing, however, the UA1 collaboration has not presented final results. Any conclusions must await their publication.

The Standard Model has been remarkably successful at describing the features of very high energy $p\bar{p}$ collisions. Most theorists believe that, for all its successes, the Standard Model is incomplete. It is the hope of the particle physics community that some aspects of a more complete theory will become apparent in the near future at the Collider or at the next generation of storage rings.

Morris Swartz, CERN

1. M. Banner *et al.*, Phys. Lett. B **118**, 203 (1982).
2. A good review of two-jet physics at the Collider is L. DiLella, CERN preprint EP/85-13 (1985), to be published in Ann. Rev. Nucl. Particle Sci.
3. P. Bagnaia *et al.*, Phys. Lett. B **144**, 283 (1984); G. Arnison *et al.*, *ibid.* **136**, 294 (1984).
4. G. Arnison *et al.*, CERN preprint EP/85-98 (1985); J. Appel *et al.*, CERN preprint EP/85 (1985).
5. G. Arnison *et al.*, Phys. Lett. B **122**, 103 (1983); M. Banner *et al.*, *ibid.* **122**, 476 (1983); Phys. Today **36**, 17 (April 1983).
6. G. Arnison *et al.*, Phys. Lett. B **126**, 398 (1983); M. Banner *et. al.*, *ibid.* **129**, 130 (1983); Phys. Today **36**, 17 (November 1983).
7. J. Appel *et al.*, CERN preprint EP/85 (1985).
8. G. Arnison *et al.*, Phys. Lett. B **147**, 493 (1984); A. Kernan, Phys. Today **38**, S.31 (January 1985).
9. P. Bangaia *et al.*, Phys. Lett. B **139**, 105 (1984).
10. G. Arnison *et al.*, Phys. Lett. B **139**, 115 (1984); J. Rohlf, Phys. Today **38**, S.34 (January 1985).

A New Generation of Computers and Lattice Gauge Theory

Lattice gauge theory is a form of gauge field theory amenable to numerical analysis. Analogous to numerical approaches to coupled partial differential equations in which one replaces differentials by discrete differences, lattice gauge theory is formulated on a space-time grid with a lattice spacing "*a*."[1] Using methods of statistical and many-body physics, one attempts to analyze the discrete system in a finite, four-dimensional box and to extract physical observables, such as the masses of particles.

Guided by experience with discrete approximations to differential equations, one expects these lattice calculations to be good approximations to the continuum field theory for excitations with wavelengths large compared to the lattice spacing but small compared to the linear dimension of the four-dimensional box. Lattice gauge theory has features that extend beyond our analogy to diffential and difference equations mentioned above. The principles of renormalization, Lorentz invariance, statistical mechanics, the phenomenology of critical points (second order phase transitions), and universality all play central roles in the formulation of lattice gauge theory.

The simulation of quark interactions along the grid lines of the lattice requires the use of the largest, fastest computers. Over the next few years we can expect considerable progress here because of the National Science Foundation's supercomputer initiative: four supercomputer centers will be established at four major universities (Cornell, Illinois, Princeton, and San Diego) for unclassified research in a wide range of disciplines.[2] This initiative will allow lattice calculations that are much more predictive, reliable, and sophisticated. In addition, algorithm development will be enhanced enormously owing to the high speeds and interactive operating systems of these machines as well as their rich software and graphics libraries.

One of the most interesting subjects in lattice gauge theory is the treatment of "dynamical fermions," that is, fermions (quarks) that can interact directly with themselves. Simulating interactions between bosons (such as gluons) is relatively easy for a computer. Simulating interactions between fermions, which obey Pauli's exclusion principle, is much more difficult. However, by using techniques borrowed from molecular dynamics and from the study of Brownian motion some progress in treating fermions has been achieved.[3] Developments over the next year will be crucial for sorting out this problem. If successful, new simulation methods for fermion problems in statistical and nuclear physics will emerge.

Physicists are also interested in building their own special purpose computers for studying lattice theories. The low price of computer chips makes it possible for a small team of physicists, students, and technicians to build a computer with a specialized architecture which should be competitive in performance to commercial supercomputers (but much cheaper) for a limited set of problems. The idea here is to build a computer which can do many operations simultaneously—a parallel processor. The lack of software, however, limits these machines to a small user community in most cases. Projects at Argonne, Columbia, and Cal Tech have been widely discussed.[4]

A wide range of problems concerning quantum chromodynamics (QCD), the prevailing theory of the strong force, are being attacked by computer studies of lattice models. These include calculating the spectrum of particle masses and the "phase" structure of a system of quarks as a function of "temperature" or chemical potential. The finite temperature and chemical potential phase transitions are new phenomena which could be studied under controlled conditions at the heavy-ion collider proposed for Brookhaven National Laboratory. At such a facility states of nuclear matter with energy densities an order of magnitude larger than ordinary nuclei could be produced, thus constituting a new phase—a relativistic plasma of quarks and gluons.

Lattice calculations can in principle make fundamental, quantitative predictions concerning this plasma and the de-confining transition between it and ordinary hadronic matter.[5] It is hoped that theory and experiment will work together on this problem to elucidate the apparent mechanism that confines quarks within hadrons. Lattice gauge theories are also being applied to models of dynamical symmetry breaking, such as the "Higgs mechanism" in the Weinberg–Salam model as well as various grand unified field theories.[6]

John Kogut, University of Illinois

1. Claudio Rebbi, Sci. Am. **248**, 54 (February 1983); *Physics News in 1982*, p. 60.
2. Physics Today **38**, 51 (May 1985).
3. J. Polonyi and H. W. Wyld, Phys. Rev. Lett. **51**, 2257 (1983); J. Kogut, J. Polonyi, J Shigemitsu, D. K. Sinclair, and H. W. Wyld, *ibid.* **53**, 644 (1984); G. Batrouni, G. Katz, A Kronfeld, G. Lepage, B. Svetitsky, and K. G. Wilson, CLNS-85/651, May, 1985.
4. Science **227**, 1024 (1 March 1985).
5. H. Satz, Phys. Rep. **88**, 321 (1982).
6. I. Montvay, Phys. Lett. B **150**, 441 (1985) and DESY report 85/005; J. Shigemitsu and K. Olynyk, Phys. Rev. Lett. **54**, 2403 (1985).

Searching for Neutrino Mass

From the standpoint of the very appealing grand unified theories of the strong, electromagnetic, and weak interactions, it is natural to expect that neutrinos have nonzero masses. The reason is that in any grand unified theory, a given neutrino is grouped (in a "multiplet") with a charged lepton (electron, muon, or tau), and with quarks of various charges. Apart from the neutrino, all the members of this multiplet are known to have nonzero masses. Thus, it is natural to expect that the remaining member of the family, the neutrino, has a nonzero mass too.

Motivated in part by this theoretical argument, many scientists have been searching for evidence of neutrino mass. One way to do this is to study decays in which a neutrino is emitted. By measuring the momenta of the particles emitted along with it, one can infer the neutrino's mass.

From observations of the electron spectrum in tritium beta decay ($^3H \to {}^3He + e^- + \nu_e$), a group in Moscow has found evidence that the mass of the electron neutrino lies between 20 and 45 eV. The range in this result is due partly to the fact that in this experiment the parent tritium nuclei are bound in complicated valine molecules. As a result, the spectrum of excited atomic final states is somewhat uncertain. Indeed, one alternative spectrum tried by the group yielded mass values below the range just quoted, but still above 9 eV.

On the basis of his own measurements K. Bergkvist of Stockholm believes that the Moscow group has overestimated the mean-square energy spread of the response function of its detector, and in consequence has overestimated the electron neutrino mass by approximately the value claimed for this mass. The Moscow claim is, of course, one of great importance, and it is being checked by a large number of tritium experiments using various techniques and a variety of source materials, some as simple as molecular or even atomic tritium, for which the final-state spectrum is well understood.

In general, one expects neutrino "mixing"; that is, the coupling by the weak interaction of more than one neutrino of definite mass to any particular charged lepton, so that nuclear beta decays need not always lead to the same neutrino. Considerable excitement was stirred by the report of evidence that a small fraction of the time, tritium beta decay yields an antineutrino with a mass of 17 keV. Unfortunately, several subsequent experiments on ^{35}S decay have not confirmed the existence of the 17 keV neutrino.

A second way to look for neutrino mass is to search for neutrino oscillation. This is the phenomenon in which, for example, a "muon neutrino"—a neutrino born in association with a muon—subsequently interacts and produces an *electron*, rather than the expected muon. One can look for this phenomenon either by looking for the production of electrons in a muon neutrino beam, or else by looking for the failure of a known flux of muon neutrinos to produce the expected number of muons. Neutrino oscillation requires neutrino masses which differ and neutrino mixing.

Numerous negative searches for neutrino oscillation, carried out at high energy accelerators, nuclear reactors, and underground laboratories, have ruled out large ranges of the neutrino mass and mixing parameters. A positive indication of oscillation has been seen at the Bugey reactor (in France), but the results of this experiment are in almost complete conflict with those of a negative oscillation search at the Gosgen reactor (in Switzerland). In addition, an unexpectedly large number of electron-producing neutrino interactions has been seen in a muon neutrino beam at CERN. A neutrino oscillation interpretation of this excess appears to be in conflict with an experiment at Brookhaven, but the matter is to be studied further in measurements planned by several groups.

Any neutrino oscillation which occurs in vacuum will be modified by the passage of neutrinos through matter. It has been pointed out that on their way out of the sun, a large fraction of the electron neutrinos generated in the solar core could turn into muon neutrinos, even if almost none do in vacuum.[1] Such large matter-induced oscillations would have very interesting effects on the solar neutrino experiments, since these detect only incoming *electron* neutrinos.

If, as grand unified theories suggest, neutrinos are massive because they are closely related to massive charged leptons and quarks, then why are they nevertheless so much lighter than these other fermions? The most popular answer to this question suggests that, unlike all other fermions, neutrinos are their own antiparticles. If so, then a neutrino can carry no information about whether it is a lepton or an antilepton, and, as a result, that lepton-number nonconserving nuclear processes such as neutrinoless double beta decay can occur. It has been shown that as long as the weak interactions conserve probability and are mediated by the exchange of singly charged or neutral weak bosons, then the observation of neutrinoless double beta decay would imply that at least some neutrinos have nonzero masses.[2] Under the simplest assumptions, the rate for this decay is proportional to the square of an effective neutrino mass. Current limits on this rate imply that the effective mass, which need not be as large as the mass measured in tritium (single) beta decay, is smaller than 10 eV and perhaps even smaller than 2 eV.

Even though we may not have already observed neutrino mass, there are good theoretical reasons to search for it, and a vigorous program of experimental searches is in progress.

Needless to say, if neutrinos do indeed have mass, the implications for both particle physics and astrophysics could be profound.[3]

Boris Kayser, National Science Foundation

1. S. Mikheyev and A. Smirnov, USSR Institute of Nuclear Research, Moscow (preprint).
2. B. Kayser, S. Petcov, and S.P. Rosen (to be published). For related results, see T. Kotani, *Proceedings of the 1984 Moriond Workshop on Massive Neutrinos in Astrophysics and in Particle Physics*, edited by J. Tran Thanh Van (Editions Frontieres, Gif sur Yvette, 1984), p. 397; J. Schechter and J. Valle, Phys. Rev. D **25**, 2951 (1982).
3. The neutrino mass experiments have been reviewed in talks delivered at the meeting of the Division of Particles and Fields, Eugene, August, 1985, by T. Bowles (decays to a neutrino), M. Shaevitz (oscillation), and M. Witherell (double beta decay), in the talk presented at the International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, August 1985 by K. Bergkvist (all experiments), and in a University of South Carolina preprint by F. Avignone *et al.* (double beta decay).

FLUID DYNAMICS

Fluid dynamics is the study of the flow of gases and liquids. Understanding fluid flow is important in many areas of science, including astrophysics, meteorology, geophysics, aeronautics, plasma physics, and biophysics. The basic equation governing fluid motion is known—Newton's second law for a continuum fluid—but this equation is notoriously difficult to solve, as are most nonlinear partial differential equations. The availability of supercomputers and the development of new techniques for investigating the dynamics of nonlinear systems has led in recent years to an increasing interest among physicists in the fundamental problems of fluid flow. Fluid instabilities and turbulence are of interest not only because of the important applications but also because recent work has shown that there are often marked similarities in the behavior of fluids and other nonlinear systems.

The Boycott Sedimentation Effect

Under the action of gravity, small solid particles will fall through a liquid in which they are suspended. As such, sedimentation plays important roles in natural phenomena such as the formation of geological deposits from estuaries or from receding flood waters. Sedimentation is also useful in industry as a means of clarifying waste water and of recovering mineral particles.

The fall velocity of a sedimenting particle is determined from a force balance between the hydrodynamic drag on the particle and its buoyant weight. Thus, microscopic particles settle only very slowly, and there exists a need for constructing simple devices that can accomplish this solid–liquid separation more rapidly. One such class of devices, sometimes referred to as "supersettlers," consists of sedimentation vessels having inclined walls. In them retention times can be reduced by an order of magnitude or more below those in corresponding vessels with vertical walls. These settlers may be composed either of a large tank containing several closely spaced tilted plates or of a narrow tube or channel inclined from the vertical (see Fig. 1). The enhancement in the sedimentation rate results from the fact that while particles can only settle onto the bottom in a channel with vertical walls, they can also settle onto the upward-facing wall in a tilted channel. These particles then form a thin sediment layer that rapidly slides down the wall toward the bottom of the vessel under the action of gravity.

The phenomenon of enhanced sedimentation in inclined channels has a long history. One of the first references to appear in the literature is attributed to physician A. E. Boycott, who in 1920 reported that "when...blood is put to stand

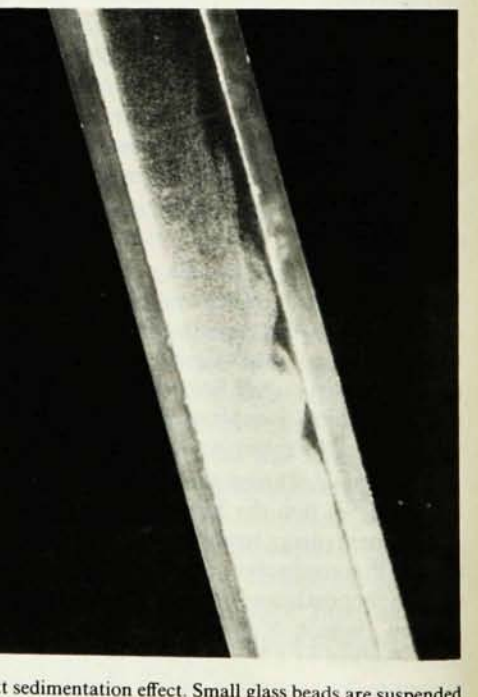

FIG. 1. The Boycott sedimentation effect. Small glass beads are suspended in a viscous oil and allowed to settle within a rectangular channel inclined from the vertical.

in narrow tubes, the corpuscles sediment a good deal faster if the tube is inclined than when it is vertical."[1] Subsequently, many investigators studied this so-called "Boycott effect" for a variety of suspensions of particles and reported that a severalfold increase in the sedimentation rate could indeed by achieved.

As an example, Davis and Birdsell at the University of Colorado have recently used the Boycott sedimentation effect to collect yeast cells from an aqueous suspension. In one experiment, they were able to harvest a yeast culture in only 30 min using an inclined settler, whereas the same separation required more than 24 hours in a conventional vertical settler.[2]

Although the Boycott effect of enhanced sedimentation has been known for many decades, only in the last few years has it been analyzed using the principles of fluid dynamics. Recent studies have been carried out at Stanford, MIT, Vienna, and Stockholm. The principal features of the flow profiles created during sedimentation within channels inclined from the vertical are described in a technical review which also lists most of the key references on the subject.[3]

One finding of particular interest is the discovery that as the particles settle a thin clear-fluid layer forms beneath the downward-facing wall of an inclined channel. This particle-free layer is buoyant compared to the bulk suspension, and the fluid within it flows rapidly to the top of the vessel. Under some conditions waves have been observed to form at the interface between the suspension and the particle-free layer. These waves grow as they travel up the vessel and often break before reaching the top of the suspension. The formation and breaking of waves along the thin clear-fluid layer is seen in Fig. 1. Evidently, the occurrence of such an instability limits the efficiency of the inclined settling process because when the waves break, fluid that has already been clarified is remixed with the suspension.

Current research on the Boycott effect is aimed at predicting the conditions under which waves along the clear-fluid layer form and grow and how their break-up affects the operation of the settling unit, and then comparing these predictions to measurements in the laboratory. This represents only one of the many exciting and ongoing fluid dynamic developments in the classical area of sedimentation.

Robert H. Davis, University of Colorado and Andreas Acrivos, Stanford University

1. A. E. Boycott, Nature **104**, 532 (1920).
2. R. H. Davis and S. A. Birdsell, Dev. Ind. Microbio. (in press, 1985).
3. R. H. Davis and A. Acrivos, Annu. Rev. Fluid Mech. **17**, 91 (1985).

Flows with Sharp Interfaces

Some of the most familiar sources of geometrical pattern formation in fluid flow arise when there is a finite jump of a material property such as density or viscosity across a sharp interface. The surface of the sea with its myriad wave motions, bubbles, and droplets is a familiar case. Fluid dynamical systems of this kind have been used frequently to provide morphological models in other fields of science, including biology and geology. In recent years there has been renewed interest in this type of flow, stimulated in part by specialized computational methods that allow one to follow deforming interfaces into highly complex flow regimes at resolutions comparable to the best laboratory experiments. In most cases the approaches used have been suggested in principle quite some time ago. The current implementations, however, have relied heavily on the availability of powerful computers, including supercomputers.

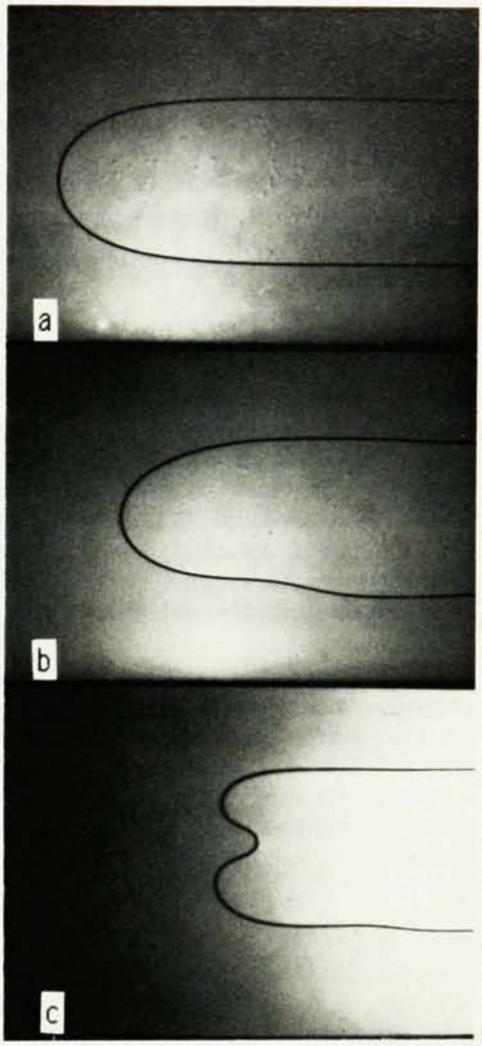

FIG. 2: The formation of "fingers" at the interface between two immiscible fluids in a Hele–Shaw cell. (a) A stable finger. (b) and (c) Unstable fingers.

Along with advances in computing ability there has been an increasing awareness of relationships between interface-dynamics problems originating in diverse fields. For example, there are important relationships between the phenomenon of dendritic growth[1]—a key problem in metallurgy—and the "fingering" that can take place at the interface between immiscible fluids of different viscosity confined in a Hele–Shaw cell, a device consisting essentially of two very close, parallel, glass plates.[2] The latter problem has been a paradigm for secondary oil recovery in petroleum engineering (where the two fluids are oil and water), and for much of the study of soil–water motion in civil engineering.

Within the physics community there is an ongoing effort to approach a wide spectrum of interface-dynamics problems from a unified point of view.[3] This has led to the creation and study of several models that are mathematically interesting and perhaps more tractable than the systems inherited from specific applications. Examples include the "local dynamics" models of dendritic growth[1,4] and diffusion limited aggregation.[5]

The central successful idea in the computational studies has been the application of so-called boundary integral methods.[6,7] Many problems of stratified flow admit idealized versions with the mathematical property that only the interface itself needs to be tracked in time. The dynamics of the fluid on either side of the interface is determined uniquely by the boundary data furnished through the displacement of the interface. Effectively this property accomplishes a reduction by one in the dimensionality of the problem. Algorithms can be constructed to take advantage of this formal simplification.

In Fig. 2 experimental results on stable and unstable single fingers in the Hele–Shaw problem are shown.[6] Steady states consisting of a single finger (a) have a substantial literature.[2,7–9] The instabilities seen in (b) and (c) are currently the object of much attention.[10] Impressive agreement between experimental and computational studies using different numerical methods can be obtained for these states.[2,7–9]

Many open questions remain. One would like to classify the various types of interfacial structures that are observed and to understand "universal" features. And, since statistical regimes with many competing interfacial structures clearly do exist, one would like to establish connections to other bodies of theory dealing with random patterns.

Hassan Aref, University of California, San Diego

1. Physics News in 1984, p. 21.
2. P. G. Saffman and G. I. Taylor, Proc. R. Soc. London Ser. A **245**, 312 (1958); R. L. Chuoke, P. van Meurs, and C. van der Poel, J. Petrol. Tech. **11**, 64 (1959).
3. L. P. Kadanoff, J. Stat. Phys. (in press).
4. R. C. Brower, D. A. Kessler, J. Koplik, and H. Levine, Phys. Rev. Lett. **51**, 1111 (1983); Proc. V'th Conf. Phys.-Chem. Hydrodyn. (1984), and references therein.
5. Physics News in 1984, p. 19; L. Paterson, Phys. Rev. Lett. **52**, 1625 (1984).
6. G. R. Baker, D. I. Meiron, and S. A. Orszag, Phys. Fluids **23**, 1485 (1980); J. Fluid Mech. **123**, 477 (1982); E. A. Overman, N. J. Zabusky, and S. L. Ossakow, Phys. Fluids **26**, 1139 (1983).
7. G. Tryggvason and H. Aref, J. Fluid Mech. **136**, 1 (1983); **154**, 287 (1985); Physical D **12**, 59 (1984).
8. P. Tabeling and A. Libchaber, University of Chicago preprint (1985).
9. J. W. McLean and P. G. Saffman, J. Fluid Mech. **102**, 455 (1981); J.-M. Vanden-Broeck, Phys. Fluids **26**, 2033 (1983).
10. C.-W. Park and G. M. Homsy, Phys. Fluids (in press); A. J. DeGregoria and L. W. Schwartz, Exxon Res. & Eng. Co. preprint (1985); D. A. Kessler and H. Levine, Schlumberger–Doll Res. Note (1985); D. Bensimon, University of Chicago preprint (1985).

PHYSICS APPLIED TO INDUSTRY

Physics in industry overlaps many discipline-oriented subdivisions, such as chemical physics, condensed matter physics, optics, polymer physics, and vacuum physics. Many items in those chapters of *Physics News in 1985* devoted to these subjects are of industrial importance. But we have chosen in this chapter to highlight research developments that are peculiarly *industrial*. In these cases, erudite physical research is motivated by the application as well as by the intrinsic understanding that can be reached about physical phenomena.

Examples of physics motivated by industrial goals range from nuclear reaction analysis in graphite-epoxy composites to optical structure resonance in aerosols, from heteroepitaxy on the surface of silicon wafers to nuclear magnetic resonance on the interior of human tissue.

There may never be a "physics industry" analogous to the chemical industry, but in 1985 physics in industry is flourishing, and the importance to technology of physical understanding has never been greater.

E. C. McIrvine, Xerox Corporation

Alloy Development Investigations Using Nuclear Reaction Analysis

The development of commercial alloys for many industrial applications has received new impetus from trace element detection techniques using nuclear reaction analysis. In a variety of alloys and composite materials the presence of a trace interstitial element or the amount of a substitutional alloying component can critically alter the mechanical properties of the material. Hydrogen in titanium alloys is a classic case of the deleterious effect that a trace element can have on the tensile strength through decohesion and crack initiation in the material. Similarly, moisture absorption and diffusion in graphite-epoxy composites leads to a lowering of the glass transition temperature of the materials, resulting in a loss of tensile strength at elevated temperature. A decrease in hardness of an aluminum–lithium alloy occurs when the alloying lithium content is depleted from the surface of the material during conventional heat treatment procedures. These are just a few examples of the problems presently under investigation by materials scientists.

Many studies have relied on detection methods that deduce the concentration of an elemental component from measurement of a related physical property, but recent development of nuclear reaction analysis methods applied to the measurement of localized elemental concentrations in alloys and composites has led to increased insight into crack initiation mechanisms as well as bonding of dissimilar alloys.

A small low-energy accelerator, delivering multiple ion-beam species, is capable of inducing a variety of nuclear reactions whose gamma-ray or particle emission rate is proportional to the concentration of the trace element within the reaction volume. Nuclear reaction analysis (NRA) techniques are especially well suited to the study of commercial alloys because a particular nuclear reaction may yield a high sensitivity measurement of a certain trace element, such as hydrogen or lithium, to the exclusion of the other alloying elements comprising the matrix. Sensitivities on the order of a few tens ppm (by weight) of hydrogen in titanium are sufficient to investigate the migration of hydrogen in certain titanium alloys under the influence of an applied stress gradient. A calibrated measurement of the hydrogen concentration level has made it possible to compare the extent of hydrogen change in a stress gradient to that predicted by thermodynamic models.[1] The capability of NRA for *in situ* measurement of the dynamics of hydrogen migrations in a stress gradient has resulted in near-room-temperature determination of the diffusivity of hydrogen in titanium alloys. Each of these studies is an important step in evaluating the role of hydrogen in crack initiation and propagation mechanisms.

Very recent interest in the development of Al–Li alloys has prompted investigations of surficial lithium loss in these alloys as a result of heat treatment processes. A finely collimated ^{3}He ion beam produces a high energy proton signature whose emission rate is proportional to the lithium concentration. Scanning the ion beam across a heat-treated Al–Li alloy specimen produces a profile of the lithium concentration for comparison to lithium loss calculations based on certain depletion models. A parametric evaluation of the lithium concentration profile under various heat treatment conditions is instrumental in ascertaining the type of heat treatment environment that produces the desired precipitation hardening of the alloy while minimizing the loss of lithium, which would cause a decrease in the microhardness in the near surface region. The rate of lithium loss in heat-treated Al–Li has been shown to be diffusion limited in a dry air environment, but the rate is considerably diminished when the exposure is done in an argon environment.[2]

Nuclear reaction analysis techniques are likely to play an increasing role in commercial alloy development programs in order to evaluate the effects of trace elements on mechanical or physical properties. The sensitivity and selectivity of these techniques for certain light elements often provide advantages over conventional methods of concentration profiling.

Richard A. Scheuing, Corporate Research Center, Grumman Corporation

1. R. L. Schulte and P. N. Adler, IEEE Trans. Nucl. Sci. **NS-30**, 1343 (1983).
2. J. M. Papazian, R. L. Schulte, and P. N. Adler, Metal. Trans. (submitted).

Structure Resonances and Modulation Spectroscopy of Aerosols

The growth, decay, and chemical evolution of aerosols are of great importance to atmospheric visibility, atmospheric chemistry, chemical vapor deposition, and combustion. Until recently these dynamics were studied only in relatively large and polydisperse ensembles over extended periods of time. Now, by a combination of pulsed modulation lasers, probe lasers, and particle levitation, it is possible to measure growth and decay of single aerosol particles and to work on nanosecond (10^{-9} sec) time scales.

Several groups have exploited optical structure resonances to study single droplets and spherical particles. These resonances occur when light waves propagating around a uniform aerosol particle can constructively interfere to give high electric field intensitives within the particle. The resonance conditions exist not only for external light excitation, but also for internally generated light exiting a particle. These structure resonances have allowed variations of aerosol particle size as small as 10 ppm to be observed via elastic light scattering,[1] fluorescence,[2] Raman scattering,[3,4] or stimulated Raman spectroscopy.[5] Chang and co-workers have observed these effects with falling monodisperse droplets, while others have used electrically and optically levitated single aerosol particles. In a further advance, the absorption spectrum of a single levitated droplet was obtained by measuring the photothermal induced evaporation of the particle.[6]

Such size modulation techniques have also been applied to small regions of polydisperse samples of solid particles. Using modest energy pulsed lasers, even solid carbon particles can be vaporized.[7] When combined with beams or sheets of probe light, modulated absorption allows high sensitivity, spatially resolved concentration measurements, while modulated light scattering permits visualization of flow patterns and relative nucleation rates.[8]

C. J. Dasch, General Motors Research Laboratories

1. A. Ashkin, J. M. Dziedzic, and R. H. Stolen, Appl. Opt. **20**, 2299 (1981).
2. J. F. Owen, P. W. Barber, P. B. Dorain, and R. K. Chang, Phys. Rev. Lett. **47**, 1075 (1981).
3. J. F. Owen, R. K. Chang, and P. W. Barber, Aerosol. Sci. Technol. **1**, 293 (1982).
4. P. W. Dusel, M. Kerker, and D. D. Cooke, J. Opt. Soc. Am. **69**, 55 (1979).
5. J. B. Snow, S.-X. Qian, and R. K. Chang, Phys. Rev. Lett. (to be published).
6. S. Arnold, M. Neuman, and A. B. Pluchino, Opt. Lett. **9**, 4 (1984).
7. C. J. Dasch, Appl. Opt. **13**, 2209 (1984).
8. C. J. Dasch, Opt. Lett. **9**, 214 (1984).

Band Gap Engineering and Heteroepitaxy on Silicon

Despite the dominant position of silicon in semiconductor electronics, its use is ultimately limited by its incompatibility with other semiconducting materials. For many years scientists have tried to combine silicon with other semiconducting materials and to form better structures on silicon. One method is epitaxy—the growth of single crystal layers on single crystal substrates. Molecular beam epitaxy (MBE) is the finely controlled evaporation of materials onto a substrate in ultrahigh vacuum. This technique requires much lower temperatures (400–800 °C for Si MBE) for epitaxial growth than standard growth techniques and, in addition, allows control of doping profiles and the interfaces between layers down to an atomic level. In "heteroepitaxy," a single crystal is created by growing single crystal layers of different materials. Through this technique, one hopes to engineer unique properties in crystals which do not occur naturally.

Considerable progress in solving this technologically important problem has been made by Bean and collaborators at AT&T Bell Laboratories over the last two years.[1,2] They have utilized the concept of strained layer heteroepitaxy.[3] The constituent semiconductor lattices do not match, but the thickness of the layers is small enough to ensure that the lattice mismatch is accommodated by strain without generating misfit dislocations at the interface. In particular, Si/SiGe heterostructures and superlattices have been grown by Bean using silicon molecular beam epitaxy. Even though the lattice constant of Ge is 4.2% larger than that of Si, Bean and his collaborators have discovered that, depending on the GeSi alloy composition, layers as thick as 1 μm can be grown on top of Si without generating dislocations. The larger GeSi lattice is simply compressed in the growth plane to match the silicon lattice spacing. A key observation was the growth of dislocation-free materials ten times thicker than predicted by equilibrium theories of dislocation formation. By overgrowing a layer of Si on the strained layer, Bean has been able to grow superlattices on the Si/SiGe system. (See Fig. 1.)

Because of the lattice mismatch strain, the thin GeSi films are under a considerable compressive stress. Recently, calculations[4] have shown that this causes the band gap, the difference in energy between valence and conduction electrons, of the GeSi strained layer films to be substantially smaller than that of corresponding bulk GeSi alloys. The growth of GeSi heterostructures on silicon thus allows one to exploit "band gap engineering" techniques such as modulation doping,[5] field effect transistors,[6] and novel photodetectors,[7] in silicon based technologies. Such heterostructure band gap engineering had previously been the exclusive preserve of III–V compound semiconductors.[8,9]

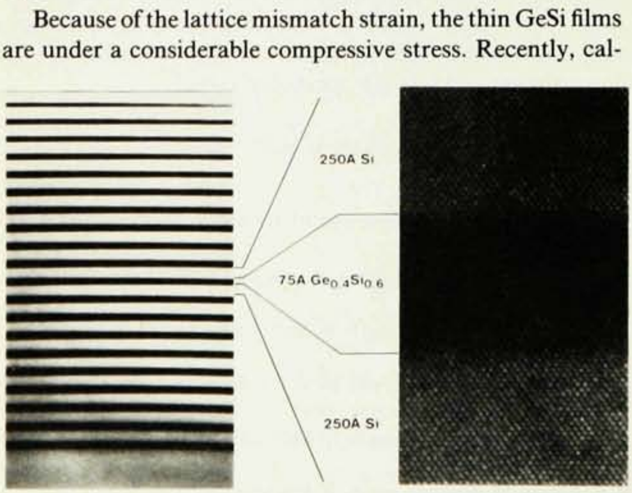

FIG. 1. A cross section of a 20-period GeSi strained-layer superlattice taken by high resolution transmission electron microscopy.

Molecular Beam Epitaxy also allows the growth of compatible metals, such as silicides,[10] and insulators as single crystals on silicon. From these some very novel device structures are emerging. Tung and his collaborators have grown very high quality single-crystal metal silicide layers on silicon.[11] A buried heterostructure of Si/$CoSi_2$/Si has been grown which demonstrates transistor action with the metal layer operated as the base.[12] Other groups at Tokyo Institute of Technology and MIT's Lincoln Labs are working on related novel high-speed devices made from MBE Si/metal/Si heterostructures.

Very high quality CaF_2, an insulator, has been grown on silicon by groups at AT&T Bell Laboratories, Tokyo Institute of Technology, and General Electric, among others.[13] Epitaxial insulators have potential as improved gate dielectrics in a device known as a MEISFET (Metal Epitaxial-Insulator Field-Effect Transistor) which has been fabricated by the AT&T Bell Laboratories group.[14] Other applications of epitaxial fluorides include dielectric isolation. Owing to the preservation of crystalline structure, epitaxial silicon can be overgrown on epitaxial films, facilitating three-dimensional integration of devices.

The possibilities opened by heteroepitaxy using MBE are many and have only just begun to be explored. The low growth temperature and control permitted by MBE are unparalleled, and will permit much further development in the area of heteroepitaxy.

V. Narayanamurti and J.M. Gibson,
AT&T Bell Laboratories,

1. J. C. Bean, L. C. Feldman, A. T. Fiory, S. Nakahara, and I. K. Robinson, J. Vac. Sci. Technol. A **2**, 436 (1984).
2. J. C. Bean, Science (to be published).
3. G. C. Osborn, J. Vac. Sci. Technol. **21**, 469 (1982).
4. R. People, Phys. Rev. B **32**, 1405 (1985).
5. R. People, J. C. Bean, and D. V. Lang, J. Vac. Sci. Technol. A **3**, 846 (1985); G. Abstreiter, H. Brugger, T. Wolf, H. Jorke, and H. J. Herzog, Phys. Rev. Lett. **54**, 2441 (1985).
6. T. P. Pearsall, J. C. Bean, R. People, and A. T. Fiory, Proc. of 167th Meeting of ECS, Toronto, Canada, May 12, 1985 (to be published).
7. A. Kastalsky, S. Luryi, and J. C. Bean, *Proceedings of the 1st International Symposium on Si MBE*, edited by J. C. Bean (Electrochemical Society, Pennington, NJ, 1985); H. Temkin, T. P. Pearsall, and J. C. Bean (to be published).
8. F. Capasso, *Proceedings of the 17th International Conference on the Physics of Semiconductors* (Springer, Berlin, 1984), pp. 1537–1543.
9. V. Narayanamurti, Phys. Today **37**, 24 (1984).
10. K. N. Tu and J. W. Mayer, *Thin Films, Interdiffusion and Reaction*, edited by J. M. Foate, K. N. Tu, and J. W. Mayer (Wiley, New York, 1978), p. 359.

11. R. T. Tung, J. M. Gibson, and J. M. Poate, Phys. Rev. Lett. **50**, 429 (1983).
12. J. C. Hensel, A. F. J. Levi, R. T. Tung, and J. M. Gibson, Appl. Phys. Lett. **47**, 151 (1985).
13. See, for example, Proc. of MRS Meeting Layered Structures, Epitaxy and Interfaces **37**, 144 (1984).
14. T. P. Smith III, J. M. Phillips, W. M. Augustyniak, and P. J. Stiles, Appl. Phys. Lett. **45**, 907 (1984).

Magnetic Resonance in Medicine

Three major themes in 20th century physics—nuclear magnetic resonance, superconductivity, and high-speed digital data processing—are combined in a medical device that continued to have accelerated clinical utilization during 1985. Approximately 200 magnetic resonance scanners—most using whole-body sized superconducting magnets—were scheduled for installation during the year. Hundreds of papers were published, and more than a dozen major meetings were held. The Society of Magnetic Resonance in Medicine meeting in London had more than 1,500 attendees and 650 papers.

The major new developments center around four areas:

(1) data regarding clinical effectiveness of the current generation of scanners;

(2) technical advances (for example, surface coils) for improved image resolution;

(3) refined pulse sequences to permit more detailed data acquisition (for example, distinguishing between proton resonance signals from fat and water molecules); and

(4) advanced studies of chemical shift spectroscopy as applied to biology and medicine.

The vast majority of current hospital examinations using NMR form a cross-sectional image of the patient's internal anatomy. The patient is placed within a magnet that contains an rf coil tuned to the proton Larmor frequency and highly linear gradient field coils. The protons in a thin slice (3 to 10 mm thick) are selectively excited by the simultaneous use of the rf and one of the gradient coils. During the free induction decay, additional gradient fields are applied to encode position information. An antenna coil detects the signal, which is sampled to provide a discrete data set. A two-dimensional Fourier transformation is used to produce the image which, in a typical case, may consist of 256×256 pixel brightness numbers.

The resolution of the images is typically 1 to 2 mm at acceptable levels of graininess. In most cases, the dominant noise source is thermal noise originating as black-body "radiation" within the patient. When it is necessary to image only a limited anatomical region, better signal-to-noise behavior and, therefore, better resolution can be achieved by the use of specially designed "surface coils" adapted to the anatomical region of interest. These coil designs have been used to achieve high resolution (for example, 0.5 mm) of regions such as the eye[1] (See Fig. 2) and spine.[2] A wide variety of antenna designs, each adapted to a particular anatomical region, will be in clinical use in many hospitals in the next year or so.

One area of intense research activity is the use of chemical shift spectroscopy to follow biochemical and metabolic processes. Much of this work centers around the study of energy metabolism using the resonance of ^{31}P nuclei. Recently, it has been possible to obtain phosphorus spectra from the human heart and, again with the use of gradient coils, to localize the origin of the signal to specific depths from the chest wall.[3] This greatly enhances the likelihood of future applications of NMR to the study of heart disease.

The proton spectrum also contains much biochemical information. The use of advanced selective pulse sequences[4] or multiple quantum phenomena[5] has made it possible to suppress the intense signal from the water protons in biological tissues by a sufficient factor to measure spectra that can be assigned to specific metabolites.

Further development of these techniques can be expected to greatly extend the application of magnetic resonance in medicine beyond the formation of gray-scale images.

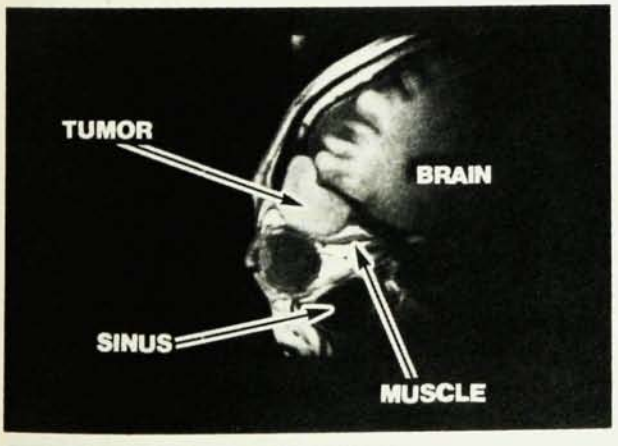

FIG. 2. Image of eye and adjacent tumor. This high resolution magnetic resonance image shows a benign tumor called a mucocele that is encroaching on the muscles responsible for eye motion. This surface coil image was made at 1.5 T. It has a 256×256 grid with a 3 mm slice thickness. The pixels are approximately 0.5 mm on a side. Reprinted, with permission, Ref. 6.

J. F. Schenck,
General Electric Research and Development Center

1. J. F. Schenck, H. R. Hart, T. H. Foster, W. A. Edelstein, P. A. Bottomley, R. W. Redington, C. J. Hardy, R. A. Zimmerman, and L. T. Bilaniuk, Am. J. Neuroradiol. **6**, 193 (1985).
2. R. R. Edelman, G. M. Skoukimas, D. D. Stark, K. R. Davis, P. F. J. New, S. Saini, D. I. Rosenthal, G. L. Wismer, and T. J. Brady, Am. J. Roentgenol. **144**, 1123 (1985).
3. P. A. Bottomley, Science **229**, 769 (1985).
4. H. P. Hetherington, M. J. Avison, and R. G. Shulman, Proc. Natl. Acad. Sci. U.S.A. **82**, 115 (1985).
5. C. L. Dumoulin, J. Magn. Reson. **64**, 38 (1985).
6. L. T. Bilaniuk, J. F. Schenck, R. A. Zimmerman, H. R. Hart, T. H. Foster, W. A. Edelstein, H. I. Goldberg, and R. I. Grossman, Radiology **156**, 669 (1985).

MATHEMATICAL PHYSICS

Mathematical physics involves the determination of the consequences of physical theories and the establishment of the properties of model systems using the standards of rigor applied in modern mathematics. More generally, mathematical physics tends to include any application of sophisticated mathematics to theoretical physics. Traditionally, this last aspect has primarily involved the theory of group representations, but more recently other areas of mathematics, especially topology and differential geometry, have been heavily used by theoretical physicists.

This year has been an extraordinary one for mathematical physics: several longstanding major open problems have been solved. For this reason, this review will discuss only progress in the rigorous study of theoretical models. I hope that reviews in future years will also discuss applications of modern mathematics to theoretical physics.

Space limitations have prevented me from discussing all the areas where there has been significant progress, such as the work of Imbrie (Harvard)[1] on the lower critical dimension for the random Ising model, or the proof[2] of asymptotic completeness in the scattering theory of a large class of multiparticle quantum systems by Sigal (Irvine) and Soffer (Caltech), or the progress in our understanding of localization in the Anderson model of electron transport in random media.[3–6]

Barry Simon, California Institute of Technology

1 J. Imbrie, Phys. Rev. Lett. **53**, 1747 (1984); Commun. Math. Phys. **98**, 145 (1985).

2 I. Sigal and A. Soffer, Bull. Am. Math. Soc. (submitted); Ann. Math. (submitted).

3 J. Frohlich, F. Martinelli, E. Scoppola, and T. Spencer, Commun. Math. Phys. (to be published).

4 S. Kotani, Proc. AMS Conf. on Random Matrices (to be published).

5 F. Delyon, Y. Levy, and B. Souillard, Phys. Rev. Lett. **55**, 618 (1985); J. Stat. Phys. Commun. Math. Phys. **100**, 463 (1985).

6 B. Simon, M. Taylor, and T. Wolff, Phys. Rev. Lett. **54**, 1589 (1985); B. Simon and T. Wolff, Commun. Pure Appl. Math. (to be published); B. Simon, Commun. Math. Phys. (to be published).

Construction of Renormalizable Quantum Fields

During the past year, the first mathematically rigorous construction of a field theory that is renormalizable but not superrenormalizable has been accomplished independently by two groups, one working at Ecole Polytechnique near Paris, and one at Harvard.

Quantum field theories normally have various coupling constants, such as the electron's charge, which can be adjusted to describe different possible physical conditions. It is often natural to try to study these theories by viewing them as perturbations of a theory where these constants are set to zero and all interactions are absent. The physical quantities in the interacting theory are then given by a formal infinite power series in the various coupling constants. It was realized in the earliest days of quantum mechanics that the individual terms in these series tend to be given by divergent integrals. That is, the integrals are over an infinite momentum space. The integrals are finite if the region of integration is limited to a finite ball; but as the size of that ball becomes infinite, the integrals also become infinite. At the level of perturbation theory, this problem is usually solved by a procedure known as renormalization. It was realized that the interactions change the value of various physical quantities, such as particle masses and charges from their input values. As the cutoff regions for the integrals are enlarged, one must adjust the input parameters to keep the physically measurable output parameters at their proper values. This forces the input parameters to go to infinity also. There are then cancellations between the two infinite quantities (input parameters and perturbation integrals) resulting in a perturbation series whose individual terms are finite.

This does not imply that one has constructed a mathematically precise theory. The problem is that there is a second somewhat subtler infinity; while each individual term of the perturbation series is finite, the series has an infinity of terms and it may happen that these series are divergent for all values of the physical output parameters. Indeed some believe that this is the case for almost all field theories that have been studied. For example, it is likely that the celebrated series for Quantum Electrodynamics (QED) diverge: the first few terms give a very good approximation of nature, but if one were to compute and sum many terms the results would diverge!

For this reason there has been considerable interest in developing nonperturbative methods and in demonstrating the internal mathematical consistency of quantum field theories, even those that cannot themselves describe nature or even a part of nature. Starting with pioneering work of James Glimm (now at NYU) and Arthur Jaffe (Harvard) in the late 1960's, a number of mathematically precise quantum fields have been constructed. Until the progress of the past year, all these models had been superrenormalizable.

On the basis of renormalization theory, one classifies field theories into three types: nonrenormalizable, renormalizable, and superrenormalizable. The first class requires one to adjust an infinite number of input parameters; many (but certainly not all) theoretical physicists feel that such theories cannot be candidates for models of nature. Superrenormalizable theories not only require one to renormalize only a finite number of input parameters but also that the output parameters have only a finite number of infinite terms. There is a sense in which the subtractions can then be handled by hand. Thus the successful construction of renormalizable theories which are not superrenormalizable represents considerable progress.

The two groups study the same model, known as the Gross–Neveu model. Many infinities are less severe in space-time dimensions smaller than four and it has been common to study such unphysical models as a kind of theorists' laboratory for understanding quantum field theory. The model is formulated in a two-dimensional space time and uses the basic interaction mechanism proposed by Fermi to describe weak interactions. There are more than one type of fermion with an internal symmetry relating them. It was discovered about ten years ago that this model is asymptotically free within the classification connected with renormalization group theory.[1] Both groups find rigorous ways of implementing the renormalization group philosophy. The results on the model have been announced[2] and fuller papers will appear soon.[3] The formal perturbation series are indeed divergent but the theory can be recovered from the series by a procedure known as renormalization.

There is an important ingredient missing in this model as compared with the Weinberg–Salam model of weak interactions and with Quantum Chromodynamics (QCD), the currently accepted model of the strong interactions. Namely, these physical models have internal gauge symmetries and the Gross–Neveu model does not. By a naive classification, QCD is nonrenormalizable, but it was realized by Gerard 'tHooft that the gauge symmetry itself causes some cancellations of infinities so that the theory is "effectively" renormalizable in four space-time dimensions and superrenormalizable in fewer dimensions. There are extra subtleties associated with gauge theories which must be overcome before one can prove that QCD is internally consistent mathematically. There has also been progress during the past few years on the construction of superrenormalizable gauge theories in fewer than four dimensions. One can hope that a synthesis of these ideas with the new progress on renormalizable theories (together with additional hard work and insight) will lead before long to the successful construction of a mathematically rigorous QCD.

Barry Simon

1. D. Gross and A. Neveu, Phys. Rev. D **10**, 3235 (1974); P. Mitter and P. Weisz, *ibid.* **8**, 4410 (1973).
2. J. Feldman *et al.*, Phys. Rev. Lett. **54**, 1479 (1985); K. Gawedzki and A. Kupiainen, *ibid.* **54**, 2191 (1985).
3. Papers to appear in Commun. Math. Phys.

Uniqueness of Transition Temperature in Multidimensional Ising Models

Phase transitions are among the subtlest phenomena in nature, and they continue to be of considerable interest to theoretical physicists. Probably the most elementary theoretical model of phase transitions is the Ising model, originally proposed in the 1920's as a model of magnetism. Because quantum effects are important in the understanding of magnetism, the Ising model is of limited use in this arena, but it has been successfully applied to the statistical mechanics of binary alloys and, because of its simplicity, it has been used to model an enormous number of other physical phenomena. Because the model possesses spontaneously broken symmetry, a critical feature of modern theories of elementary particle physics, the study of it and its relatives has been of considerable interest to high energy theoretical physicists. During the past year, Aizenman (Rutgers) has solved a long standing problem concerning the properties of the Ising model in three or more space dimensions.[1,2]

The Ising model approximates nature by using a discrete lattice. At each site of the lattice, one imagines, sits an atom, which can be in one of two states: spin up or spin down, in the magnetic picture that we will use (or, equivalently, the atom can be of type A or of type B in the binary alloy picture). There are short range interactions between the spins which tend to make nearby spins point parallel and one computes the properties of the bulk matter using the rules of classical statistical mechanics. The subtleties arise from the facts that despite the presence of thermal fluctuations, the short range interactions are able to conspire to produce bulk magnetization and that the transition between a magnetized state and an unmagnetized state as the temperature is varied is sharp and accompanied by singularities in physical quantities such as the specific heat.

One measure of the tendency of widely separated sites in the system to act cooperatively is a quantity known as the two-point correlation function. It is a function of the lattice site and measures the correlations between the spin at that site and one at a conveniently chosen origin. Lack of magnetization is indicated by the correlation function decaying to zero as the sites become widely separated, indicating, in turn, the lack of correlation between distant spins. When magnetization is present, in contrast, the two-point function approaches a nonzero value. One measure of the sharpness of the transition between the magnetized and unmagnetized states concerns the rate of decay of the two-point function in the regime where it decays to zero. What Aizenman proved is that the model in three or more dimensions possesses a transition temperature T_c, so that for temperatures below this transition temperature the system is magnetized and the correlations approach a nonzero value, while for temperatures above T_c the correlations decay at an exponential rate. *A priori*, there could be an intermediate temperature range where correlations only decayed at a polynomial rate; the physics would be different in this intermediate range. There would then be two transition temperatures at the top and bottom of this range; the problem solved by Aizenman is therefore often taken as a demonstration of the uniqueness of the transition temperature in the Ising model.

The problem is subtle: For a two-dimensional model whose spins point in an arbitrary direction in the plane rather than only pointing up or down ("plane rotor" models), it has been rigorously proven[3] that there is a region where the two-point function decays to zero, but only at a polynomial rate (this is the celebrated Kosterlitz–Thouless transition[4]). It has even been proven that for two-dimensional models whose spins can point in a large but finite number of possible directions, there are two distinct transition temperatures with an intermediate "Kosterlitz–Thouless phase." So, the problem solved by Aizenman is sometimes called "the lack of an intermediate phase in the Ising model."

One critical element of Aizenman's analysis is to carefully analyze the manifestation of the phase transition in a very large but finite volume. This notion is related to recent work on "finite size scaling," which served as a partial motivation for Aizenman's work.[5] Important roles are also played by the classical Ising approximation of Griffiths–Simon,[6] the Gaussian domination inequality of Frohlich *et al.*[7] and by the random walk approach to correlation inequalities,[8] especially a result of Aizenman and Graham.[9]

As a by-product of his analysis, Aizenman has also obtained an algorithm for the numerical computation of a convergent sequence of lower bounds on T_c which complement the upper bounds obtained by Simon.[10] He has also demonstrated the continuity of T_c as various parameters are varied and has placed rigorous bounds on various critical exponents.

Barry Simon

1. M. Aizenman, Phys. Rev. Lett. **54**, 839 (1985).
2. M. Aizenman, contribution to *Statistical Physics and Dynamical Systems, Rigorous Results*, edited by J. Fritz, A. Jaffe, and D. Szasz (Birkhauser, 1985).
3. J. Frohlich and T. Spencer, Commun. Math. Phys. **81**, 527 (1981).
4. J. M. Kosterlitz and D. Thouless, J. Phys. C **6**, 1181 (1973).
5. K. Binder, M. Nauenberg, V. Privman, and A. Young (USCS preprint).
6. R. Griffiths, J. Math Phys. **10**, 1559 (1969); B. Simon and R. Griffiths, Commun. Math. Phys. **33** 145 (1973).
7. J. Frohlich, B. Simon, and T. Spencer, Commun. Math. Phys. **50**, 79 (1976).
8. M. Aizenman, Commun. Math. Phys. **86**, 1 (1982); D. Brydges, J. Frohlich, and T. Spencer, *ibid.* **83**, 123 (1982).
9. M. Aizenman and R. Graham, Nucl. Phys. B **225**, 261 (1983).
10. B. Simon, Commun. Math. Phys. **77**, 111 (1980).

Stability of Relativistic Matter

One of the reasons that quantum mechanics was invented was to solve the problem of the lack of stability of atoms in classical physics. In the 1930's it was realized by Onsager (who later received the Nobel prize in Chemistry for his work on irreversible thermodynamics) that this is not the end of the story: One also needs to examine the stability of bulk matter. Specifically, the stability of an isolated atom implies that a fixed number N of atoms will not collapse indefinitely, but it is not clear that as N increases the system will not decrease in size. Such a decrease in size is precisely what happens in nature owing to gravitational forces. However, because the gravitational force is so weak compared to the other fundamental forces of nature, we do not see the evidence for this effect until one has a large amount of matter: gravitational collapse is unimportant for terrestrial physics but obviously crucial for celestial physics.

The electrostatic force between two electrons is roughly 10^{40} times the gravitational force between them, so if there were electrostatic collapse it would be a rather prominent aspect of nature. Since it is not observed, one should be reasonably sure that matter is stable: Onsager asked if this stability was a consequence of quantum theory or if some other aspect of nature plays a role. Stability of a system of electrons and nuclei interacting via Coulomb forces was proven within the framework of nonrelativistic quantum theory almost 20 years ago. During the past year, there has been progress in our understanding of this important result, and, in particular, the first proof was published that stability still remains true when the nonrelativistic quantum theory is replaced by its relativistic counterpart.

It was realized that the lack of electrostatic collapse is equivalent to the binding energy being an extensive quantity, that is, to the total binding energy of a system of electrons and protons growing proportionally to their number. This statement was first proven by Dyson (Institute for Advanced Studies) and Lenard (Indiana) using the fact that electrons are fermions.[1] Indeed, if electrons were bosons, bulk matter would collapse (to sizes determined by nuclear masses for fermionic nuclei, and indefinitely for bosonic nuclei)! Unfortunately, the upper bound they obtained on the binding energy per particle was about 10^{15} Ryd (1 Ryd equals 13.6 eV), so that while their result implied that bulk matter does not collapse indefinitely, it would allow collapse to an absurdly small size. Substantial improvements in the proof were obtained by Federbush (Michigan)[2] and Lieb (Princeton) and Thirring (Vienna).[3] In particular, the latter authors obtained an upper bound on the binding energy per electron of "only" somewhat more than 20 Ryd. A clear summary of these issues can be found in the review article by Lieb.[4]

There has been recent interest in the question of the stability of matter when the nonrelativistic kinetic energy $p^2/2m$ is replaced by its relativistic analog. It is not hard to show that relativistic stability for any value of the mass implies stability for all m, so it is convenient to take m = O, in which case the total energy is scale covariant, that is, that both the kinetic and potential energies transform in the same manner under a change of length scale. This scale convariance implies there is a significant dimensionless constant in the problem, namely the fine structure constant α. Stability cannot occur for all values of α, and at best one can only have stability if $Z\alpha$ is less than some critical value $(Z\alpha)_{\rm crit}$. Herbst (Virginia) determined the critical value of $Z\alpha$ for a single electron to be $2/\pi$, so that one knows that if $(Z\alpha)_{\rm crit}$ is finite, it must be no more than $2/\pi$.[5] Daubechies (Brussels) and Lieb showed that for the case of one electron and several centers, there are lower bounds consistent with relativisitic stability, and they focused interest on the general problem.[6] Moreover, they pointed out that if one discusses the problem with general nuclear charges Z, one needs to consider as separate parameters both and α and $Z\alpha$.

The problem of showing that there is some α for which relativistic stability holds as recently solved by Conlon (Missouri).[7] As with the original Dyson–Lenard result, the constant Conlon gets is incredible: he obtains a lower bound for α_{crit} of 10^{-200}. Conlon uses ideas of Federbush, Lieb–Thirring, Maria and Thomas Hoffmann-Ostenhoff (Vienna), and some deep mathematical ideas of Fefferman (Princeton) and Phong (Columbia). (The Fefferman–Phong work is reviewed in Ref. 8.)

Fefferman and de la Llave have succeeded in simplifying and improving Conlon's results by heavily exploiting the scale covariance of the problem.[9] When $Z = 1$, they have shown that α_{crit} is greater than $1/(2.06\pi)$, which is not too far from the Herbst upper bound. There is a simple relation between the two stability problems (nonrelativistic and relativistic), so that a lower bound on α_{crit} yields an upper bound on the binding energy per electron in the nonrelativistic problem. In particular, Fefferman obtains nonrelativistic stability with a constant only about twice the best constant obtained by Lieb. If one can prove that $\alpha_{crit} = 2/\pi$, the Herbst value (which is certainly possible), one would have nonrelativistic stability with a constant of only a few Rydbergs!

Barry Simon

1. F. Dyson and A. Lenard, J. Math. Phys. **8**, 423 (1967); **9**, 698 (1968).
2. P. Federbush, J. Math. Phys. **16**, 706 (1975).
3. E. Lieb and W. Thirring, Phys. Rev. Lett. **35**, 687 (1975).
4. E. Lieb, Rev. Mod. Phys. **48**, 553 (1976).
5. I. Herbst, Commun. Math. Phys. **53**, 285 (1977); **55**, 316 (1977).
6. I. Daubechies and E. Lieb, Commun. Math. Phys. **90**, 511 (1983).
7. J. Conlon, Commun. Math. Phys. **94**, 439 (1984).
8. C. Fefferman, Bull. Am. Math. Soc. **9**, 129 (1983).
9. C. Fefferman and R. de la Llave (Princeton preprint).

MEDICAL PHYSICS

Mammography and Medical Physics

Breast cancer is the most frequently occurring female cancer. Over 110 000 new cases will occur in 1986. One of every 11 women born in the United States today will develop breast cancer during her lifetime. Since advances in surgery and other treatments have not significantly altered the mortality rate during the past 30 years, the principal hope for improvement lies in the early detection of minimal breast cancer, less than 5 mm in diameter. Minimal cancer, detected before metastasis can occur, is readily curable by existing therapy. At present, mammography (x-ray examination of the breast) properly performed is the most consistently accurate and reliable means of detecting such minimal, nonpalpable breast cancers.[1]

Over the past 15 to 20 years, the quality of mammography has improved greatly and the associated radiation levels markedly reduced owing to the contributions of medical physicists. Some of the improvements include better x-ray tubes, improvements in the x-ray units and their geometric arrangement, introduction of new more efficient image receptors, and invention of devices that reduce the amount of scattered radiation imaged. In addition, several physicists have analyzed the imaging process and the various factors that determine image quality in mammography.[2-8]

Early mammography examinations (before 1970) were performed with a conventional tungsten target x-ray tube and fine-grain, relatively insensitive industrial x-ray film.[9] Just prior to 1970 new x-ray tubes were introduced for mammography. These employed a molybdenum target, a thin beryllium exit window, and molybdenum filter over the window.[10] The spectra from such tubes, when operated at a peak potential of about 30 kV, were dominated by the K lines of molybdenum which occur in the region just below 20 keV, a near ideal energy range for obtaining good differentiation between tumors and breast tissue in mammograms. Further refinements included the introduction of "microfocal spots" (x-ray focal spots less than 0.2 mm) in 1977 which resulted in increased spatial resolution when geometric magnification techniques were used.[11]

The x-ray machines introduced in the 1970's produced greater x-ray intensities allowing reduced exposure times and a resulting decrease in unsharpness caused by patient motion. These x-ray machines, which were designed specifically for mammography, employed smaller x-ray focal spots and improved imaging system geometries, and rotation capabilities which allowed more precise breast positioning. The former resulted in improved imaging system resolution and the latter permitted one to better image the glandular tissue in which cancers tend to arise, especially that along the chest wall.

The most dramatic advances that have occurred during the past two decades was the introduction of two types of mammographic image receptors. The first was an electrostatic imaging technique similar to that used in photocopy machines.[12] Xeroradiography, as it is called, resulted in im-

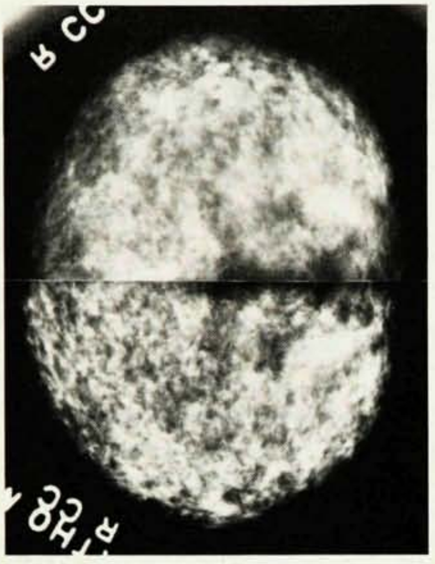

FIG. 1. Comparison of breast images obtained (a) with and (b) without scatter control. The same x-ray tube voltage, beam quality, and screen–film combination was employed for both.

ages of improved diagnostic accuracy at reduced radiation levels. Mammographic exam radiation levels were still further reduced with no loss in diagnostic accuracy with the introduction of mammographic intensifying screen–film combinations.[13] Screen–film and xeroradiographic image receptors have both found wide spread acceptance in the radiology community and provide similar accuracy in detecting early cancers. Both approaches have been improved since their introduction. For example, more recently introduced screen–film combinations achieve better images with a small fraction (approximately 1/4) of the radiation required by the first system. Another important and more recent development was the introduction of scatter control devices which provided improved image contrast.[14,15] An example of the improvement that results with efficient scatter control is shown in Fig. 1.

Medical physicists have made other contributions that have improved the acceptance and quality of mammography. They have designed appropriate patient substitutes of "phantoms" for evaluations of image quality.[16,17] They have also defined the most appropriate dose parameters for monitoring and have evaluated epidemiological data in order the estimate the small carcinogenic risks associated with the use of x rays in mammography.[18] Furthermore, they have provided benefit/risk analyses of recommended examination schedules of mammography screening programs.[19]

In the coming years, additional new and improved techniques introduced by physicists may provide more accurate and sensitive diagnosis of early breast cancer. These include nuclear magnetic resonance imaging, ultrasound imaging, and digital radiography.

Lawrence N. Rothenberg, Memorial Hospital, MSKCC, New York, and Gary T. Barnes, The University of Alabama at Birmingham

1. A. B. Miller and R. D. Bulbrook, Screening for Disease Screening, Detection and Diagnosis of Breast Cancer, Lancet 1982; May 15th pp. 1109–1111.
2. A. G. Haus, K. Doi, J. T. Chiles, K. Rossmann, and R. A. Mintzer, Invest. Radiol. **10**, 43 (1975).
3. R. F. Wagner, in *Breast Carcinoma—The Radiologist's Expanded Role*, edited by W. W. Logan (Wiley, New York, 1977), pp. 69–71.
4. G. T. Barnes and I. A. Brezovich, in *Breast Carcinoma—The Radiologist's Expanded Role*, edited by W. W. Logan (Wiley, New York, 1977), pp. 73–81.
5. E. P. Muntz, Med. Phys. **6**, 110 (1979).
6. R. J. Jennings, R. J. Eastgate, M. P. Siedband, and D. L. Ergun, Med. Phys. **8**, 629 (1981).
7. P. P. Fatouros, Med. Phys. **9**, 819 (1982).
8. G. T. Barnes and D. P. Chakraborty, Radiology **145**, 815 (1982).
9. L. Stanton, D. A. Lightfoot, J. J. Boyle, and J. E. Cullinan, Radiology **81**, 1 (1963).
10. J. Gershon-Cohen, M. B. Hermel, and J. W. Birsner, Am. J. Roentgenol. **108**, 424 (1970).
11. E. A. Sickles, K. Doi, and H. K. Genant, Radiology **125**, 69 (1977).
12. J. N. Wolfe, Radiology **91**, 231 (1968).
13. B. J. Ostrum, W. Becker, and J. H. Isard, Radiology **109**, 323 (1973).
14. M. Friedrich and P. Weskamp, Medicamundi **1**, 29 (1978).
15. M. A. King, G. T. Barnes, and M. V. Yester, in *Reduced Dose Mammography*, edited by W. W. Logan and E. P. Muntz (Masson, Paris, 1979), pp. 243–252.
16. R. E. Snyder, M. E. Masterson, D. W. Miller, R. L. A. Kirch, L. N. Rothenberg, G. R. Hammerstein, and J. S. Laughlin, in *Breast Carcinoma—A Radiologist's Expanded Role*, edited by Wende W. Logan (Wiley, New York, 1979), pp. 167–176.
17. L. Stanton, T. Villafana, J. L. Day, and D. A. Lightfoot, Invest. Radiol. **13**, 291 (1978).
18. G. R. Hammerstein, D. W. Miller, D. R. White, M. E. Masterson, H. Q. Woodard, and J. S. Laughlin, Radiology **130**, 485 (1979).
19. R. P. Chiacchierini and F. E. Lundin, in *Reduced Dose Mammography*, edited by W. W. Logan and E. P. Muntz (Masson, Paris, 1979), pp. 61–76.

Nuclear Medicine Tomography

Mankind has always been intrigued by the prospect of gaining knowledge about the contents of a container (mummies, geodes, or the human body) without disrupting or otherwise causing damage to the container. In ordinary planar medical imaging (nuclear medicine, x-ray) the three dimensionality of the body is reduced to two dimensions in a computer or film image. But often there is important information hiding in that compressed third dimension.[1]

The earliest attempts at deriving depth information were moderately successful technically but unsuccessful clinically. The rectilinear scanner, by virtue of its highly focused collimator, performs focal-plane blurring tomography. That is, structures lying near the focal plane of the collimator are in relatively sharp focus but all structures above and below the focal plane are out of focus and thus blurred. The tedium of constructing multiple scans at multiple focal plane depths rendered this technique useless for tomography. The next significant innovation in focal-plane tomography was the multiplane tomography scanner, invented by Hal Anger and produced commercially as the Searle Pho/Con. The Pho/Con consisted of two small gamma cameras, each equipped with a focusing collimator, which were scanned above and below the patient in the same manner as for rectilinear scanning. A computer was used to manipulate the data and produce six focal-plane tomographic longitudinal slices from each camera.

Focal-plane tomography has the inherent limitation that all of the gamma rays coming from the patient's body appear in the image, some in focus but most of them blurred. The *contrast* between the in-focus and out-of-focus regions was not a substantial improvement over planar imaging. Oldebdorf, Kuhl, Cormack, Hounsfield, and other pioneers developed computed tomography (CT) techniques for isolating a "slice" of interest from overlying and underlying tissues, thus greatly increasing the contrast and improving lesion detectability.[2] It is ironic to note that the very earliest experiments on CT were conducted with radionuclides, yet it was x-ray CT which was brought to commercial fruition first. But nuclear medicine has worked steadily at developing emission CT techniques and is now making important advances in two primary areas of CT.

All forms of CT require the establishment of ray sums passing throughout the volume of tissue to be imaged. In x-ray CT a ray sum is defined as the beam transmission along a line drawn from the x-ray focal spot on one side of the patient to a detector on the opposite side of the patient. In emission CT the gamma ray source is within the patient's body. In single photon emission computed tomography (SPECT), the ray sum is defined by the collimator holes on the detector rotating around the patient. In positron emission tomography (PET) the annihilation radiation formed when a positron combines with an electron forms a ray sum when both photons strike opposed detectors arranged in a ring around the patient. A powerful minicomputer acquires the data and produces tomographic transverse slices, which can be manipulated to form other arbitrary slices if a large enough body volume has been imaged.

Most SPECT units to date have been large crystal gamma cameras mounted on a gantry which permits rotation of the camera around the patient. Multiple detectors can be used to reduce the imaging time so that rapid physiological processes can be followed; ring-type detectors are currently under development. At the present time instrumentation is at a fairly advanced stage and progress in SPECT awaits the introduction of new radiopharmaceuticals tailored specifically for SPECT. The total cost of a SPECT imager, including computer, is in the range of $250,000–$400,000.

PET imaging has been performed for many years in a few major medical centers, and it has been proved to be of great value in biochemical research.[3] Clinical applications of PET are beginning to appear and should proliferate as more PET imagers are put into operation. The major sticking point of PET imaging is the necessity to have a cyclotron located in the same area as the imager in order to use the short-lived nuclides of oxygen, nitrogen, and carbon. Two advances are occurring which are addressing this problem. First, Ga-68 and Rb-82 are now available from generator systems, similar in concept to the Tc-99m and Kr-81m generators currently in use in planar imaging. The parent half-lives are sufficiently long that it is quite feasible to use them clinically. Second, the size and price of cyclotrons suitable for producing the important positron emitters have been shrinking slowly but surely. Dedicated radionuclide production cyclotrons can be purchased from several vendors and can be installed in small room with virtually no additional shielding needed. The total cost for a small cyclotron and PET imager, not including any building or room modifications, is in the range of $2–$3.5 million.[4]

Anthony R. Benedetto, University of Texas Medical Branch, Galveston, Texas

1. *Physics of Nuclear Medicine—Recent Advances*, edited by D. V. Rao, R. Chandra, and M. C. Graham, 1983 AAPM Summer School (American Institute of Physics, New York, 1984), pp. 84–99, 384–497.
2. W. Swindele and H. H. Barrett, Physics Today **30**, 32 (December, 1977).
3. M. M. Ter-Pogosian, M. E. Raichle, and B. E. Sobel, Sci. Am. **243**, 170 (October, 1980).
4. H. N. Wagner, Jr., J. Nucl. Med. **26**, 679 (1985).

NUCLEAR PHYSICS

Advances in the fundamental understanding of the properties of nuclear constituents and the forces that bind them, along with improvements in experimental capabilities have recently led to a new intellectual vitality in this field. The increasing overlap between nuclear physics and other neighboring disciplines, especially particle physics, astrophysics, and atomic physics, has provided new breadth and diversity to the problems that are concerning nuclear physicists.

In the study of nuclear structure precision electron scattering, studies have indicated that nuclear constituents do not have exactly the same characteristics as free nucleons. Understanding these phenomena in terms of the properties of the nuclear medium represents a significant challenge for the future. In another area of nuclear structure studies, investigations into the question of how nuclei adapt to very high angular momenta has provided a framework in which to study the coupling between single particle and collective degrees of freedom in the nucleus.

During the past few years the particle physics community has shown that nucleons are composite particles composed of quarks and gluons whose interactions appear well described by a theory of the strong interaction called Quantum Chromodynamics (QCD). This very successful representation for nucleons has led to intense theoretical speculations as to whether relativistic heavy ion collisions could produce, for a brief instant, a qualitatively new form of nuclear matter in which the temperature and density are large enough to cause the dissolution of the nucleon and generate a plasma of free quarks and gluons extending over a volume of several hundred cubic fermis. At Brookhaven National Laboratory a project is now underway to connect their tandem Van de Graaff accelerator with the Alternating Gradient Synchrotron in order to provide 15 GeV/nucleon beams of ^{16}O and ^{32}S ions. When available in late 1986 these beams, along with 200 GeV/nucleon ^{16}O beams expected from a similar project at the CERN SPS facility, will begin to provide the first tests of these ideas. In the meantime, experimental and theoretical work has continued utilizing data from the Lawrence Berkeley Laboratory Bevalac accelerators to try to determine important parameters of the equation of state for nuclear matter.

Since the development and confirmation of the so-called "Standard Model" for describing the electroweak and strong nuclear forces there has been growing activity in both the particle and nuclear physics communities to search for violations of the Standard Model predictions as a way of better understanding the forces of nature at an increasingly fundamental level. In nuclear physics much of this activity has concentrated on the measurement of neutrino properties, including neutrino scattering, attempts to measure neutrino masses, and searches for possible neutrino oscillations. A major advance in this area has been the development of a new neutrino scattering facility at the Los Alamos Meson Physics Facility (LAMPF) and the first measurement of the scattering of electron neutrinos from electrons. The initial data have demonstrated the existence of a postulated interference term in the scattering, consistent with predictions of the Standard Model, thus providing another impressive success for the Standard Model.

In another interface area, nuclear and atomic physicists have been searching for several years for a source of positrons that were expected from the "supercritical" electric fields that could be produced in an atom with atomic number greater than about 173. These positrons have been identified in collisions between actinide beams and targets using the heavy ion accelerator at the Gesellschaft für Schwerionenforschung (GSI) lab in West Germany. In these experiments, completely unexpected sharp lines of positrons were found. Speculations on the origin of these lines range from the postulate of long-lived nuclear molecules, to a new unexpected particle, to possible new effects in quantum electrodynamics. None of these speculations is without inconsistencies but the experimental existence of the lines seems certain.

These are only a few representative examples of current forefront activities in nuclear physics. More details on these examples are contained in the following reports.

H. C. Britt, Los Alamos Scientific Laboratory

Nuclear Dynamic Response Function

The motion and structure of nucleons inside nuclei can be studied by electron scattering. The cross section for intermediate-energy electron scattering from several light nuclei[1] is shown in Fig. 1. The data were recorded at the MIT-Bates Laboratory using a 730 MeV electron beam. The typical energy transfer (about 100 to 400 MeV) is well above that needed for ejecting nucleons and indeed is sufficient to excite a nucleon to a resonant condition known as a Δ state. The typical momentum transfer (about 500 MeV/c) is large compared with the average nucleon momentum in the target. Under these "deep inelastic" conditions, we anticipate that the nuclear response function will be dominated by quasifree scattering from individual nucleons. This simple picture of the reaction is supported by the appearance of the two broad structures in Fig. 1 centered very close to the energy loss appropriate for free-space elastic electron–nucleon scattering and excitation, respectively. The universality of the response function provides additional support for the simple idea of a dominant single-particle process. Consequently, we can now proceed to a more detailed analysis of the shape and magnitude of the peaks to learn about the nuclear momentum distribution and about modification of hadron structure caused by interaction with neighbors in the nuclear medium.

The position and width of the quasielastic peak are well understood in terms of the average nuclear potential. First, the position of the peak, at an energy loss of about 20 MeV greater than that expected for a free stationary proton, characterizes the strength of the binding nuclear potential. Second, the width of the quasielastic peak provides a direct measure of the nuclear "Fermi momentum," the momentum of the nucleons within the nucleus.

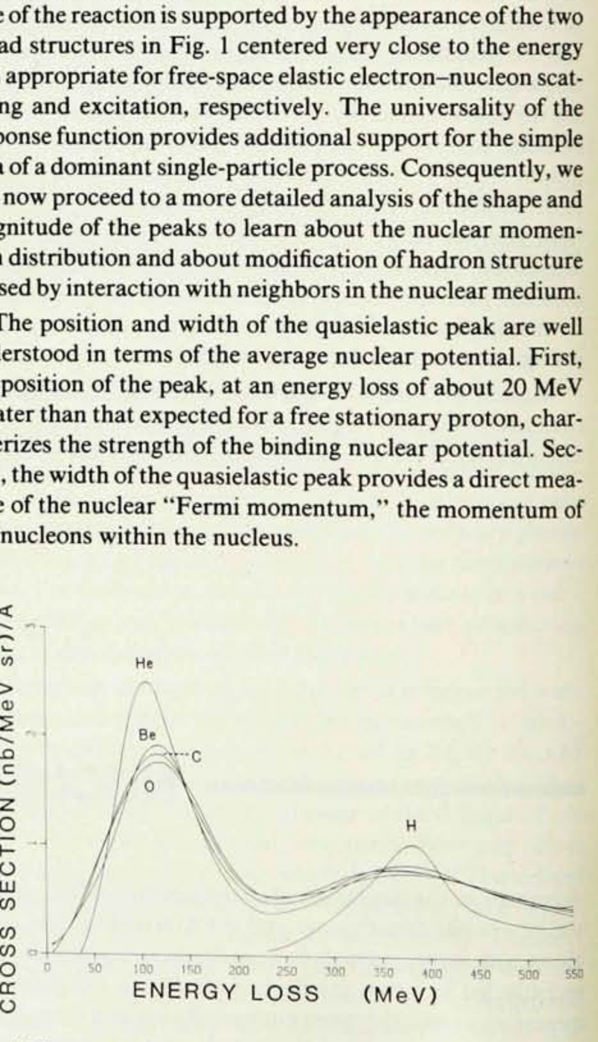

FIG. 1. The cross section for intermediate-energy electron scattering from several light nuclei.

That part of the scattering which corresponds to the electron's scattering from a nucleon's electric charge can be separated out, and this has revealed a major surprise.[2] Only about two-thirds of the scattering strength expected is found experimentally. This is especially surprising since the total strength for charge scattering would, *if* the internal nucleon dynamics were inactive, be given (with small corrections) by the measured electron–proton cross section and total nuclear charge. The possibility that this is not so is exciting. It suggests that the interplay between nucleon and nuclear degrees of freedom revealed by the EMC effect[3] may play a more important role in "low energy" phenomena than previously realized. (See *Physics News in 1984*, p. S34.) The EMC effect is the experimental observation, first made with very high energy muon beams at the CERN laboratory in Geneva, that quark momentum distributions are modified in nuclei. Specifically, they are modified in a manner which suggests an appreciably larger quark confinement scale in regions of higher nuclear density. By examining the energy and angular distribution of nucleons emitted for fixed momentum and energy transfer, new measurements should specify the dominant reaction processes responsible for the diminished strength.[4]

The second peak in Fig. 1 corresponds to excitation of Δ states. We see that the nuclear response is nearly the same for nuclei with a mass number larger than 4, but very different from that for a free proton. The peak position is at a smaller energy loss than that for a proton, indicating that the Δ sees a weaker binding potential than does the nucleon. The focus of current work is on understanding how the Δ interacts with the other nucleons or clusters of nucleons in the nucleus. Such questions involving the interplay of nuclear and nucleon degrees of freedom are central to furthering our understanding of the intermediate- and short-range nuclear force, both under normal conditions and in dense matter.

Ernest Moniz, Massachusetts Institute of Technology

1. J. S. O'Connell *et al.*, Phys. Rev. Lett. **53**, 1627 (1984).
2. Data for ^{12}C are presented in P. Barreau *et al.*, Nucl. Phys. A **402**, 515 (1983).
3. J. J. Aubert *et al.*, Phys. Lett. B **123**, 275 (1983); R. G. Arnold *et al.*, Phys. Rev. Lett. **52**, 727 (1984).
4. Data for ^{12}C are presented in H. Baghaei *et al.*, *Bates Linear Accelerator Center Annual Report*, edited by G. D. Nixon, 1985, p. 65.

The Nuclear Equation of State

High energy heavy ion collisions offer the unique opportunity of probing the properties of nuclear matter at extremely high densities and temperatures where novel, exotic forms of hadronic matter may exist. A knowledge of the nuclear equation of state, in addition to its intrinsic interest, is also of prime importance for the understanding of parts of the universe remote in space and time, such as the big bang, supernova explosions, and the interior of neutron stars.

Direct investigation of the nuclear equation of state has begun recently with the availability of beams of heavy nuclei with energies up to 1 GeV/nucleon at the Bevalac accelerator at LBL, Berkeley. These nuclei are so fast that the nucleons participating in the collision cannot escape from the interaction volume—hence they pile up and the nuclear medium becomes highly excited and strongly compressed. The high pressure generated in a collision event results in a rapid subsequent expansion of the nuclear material yielding large numbers of pions, nucleons, and light nuclei. The distributions of these emitted particles can be used to diagnose the characteristics of the original hot, dense matter. Observable compression effects are the collective sidewards flow and the dependence of the pion multiplicity on the nuclear compression energy predicted theoretically by nuclear fluid dynamics.[1] They both are the result of the high pressure buildup, which causes a large transverse momentum transfer and a change in the temperature of the system.

Recently, both effects have been observed experimentally by two collaborations[2–4] between the Gesellschaft fur Schwerionenforschung GSI, West Germany, and LBL (see *Physics News in 1984*, p. S41). The first group developed a new multiparticle electronic detector system called the Plastic Ball,[2] which enables the simultaneous determination of the total number of particles emitted in a particular collision event, as well as their respective energies, thus allowing for complete event reconstructions. The GSI/LBL collaboration found a puzzling difference between near central collisions (events with high associated multiplicity) and those reactions with larger impact parameters (a smaller number of ejectiles). A clear sidewards emission pattern was observed for the former events in the system Nb + Nb, while the less central reactions result in forward peaked angular distributions.[2] Quite analogous results were obtained in a streamer chamber experiment[3] for the reaction Ar(0.8 GeV/N) + Pb. More recently collisions of gold on gold have been studied and collective flow effects are found to be even more strongly pronounced in this system. These pioneering experiments established a collective fluid-like behavior, the key mechanism for the creation and study of dense and hot matter in high energy nuclear collisions.

These data represent a challenge to any microscopic theory: The cascade approach neglects the repulsive compression potential and assumes that nuclear collisions proceed via a sequence of independent free space nucleon–nucleon collisions.[5] Even in central collisions it predicts forward peaked angular distributions, in contrast to the data. Recently a microscopic theory of heavy ion reactions has been developed which incorporates a "stiff" equation of state (one with a high compression constant) and this does account for the large sidewards flow angles observed experimentally.[6] Additional evidence for the stiff equation of state comes from a novel momentum analysis performed for the system Ar + KCl at 1.8 GeV/nucleon.[7]

Further support for a stiff equation of state comes from the pion multiplicities that have been measured event-by-event in the streamer chamber for near central collisions of Ar (0.4–1.8 GeV/N) + KCl. The pion yields calculated from the cascade model[5] (which neglects the compression potential) drastically overestimate the data. It has been conjectured[4] that the difference between the measured pion yields and the cascade simulations is due to the inherent neglect of the compression energy in the cascade approach and thus may be used to extract the nuclear equation of state at high densities. In fact, the nuclear equation of state extracted from this discrepancy rises rapidly in the density regime accessible in the experiment. A comparison with the microscopic theory again reveals the need for the stiff equation of state.

Much progress has been made both experimentally and theoretically in the methods of studying relativistic heavy ion collisions. Our first glimpse of the nuclear equation of state seems to reveal surprisingly large incompressibilities at densities about 204 times the ground state density. Over the next decade, even more difficult problems will be tackled when going into the ultrarelativistic regime at accelerators at CERN and Brookhaven.

Horst Stöcker, Michigan State University and University of Frankfurt, West Germany

1. W. Greiner and H. Stöcker, Sci. Am. (January 1985); H. Stöcker, W. Greiner, and W. Scheid, Z. Phys. A **286**, 121 (1978); G. Buchwald *et al.*, Phys. Rev. Lett. **52**, 1594 (1984).
2. H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Lohner, B. Ludewigt, A. M. Poskanzer, T. Renner, H. Riedesel, H. G. Ritter, A. Warwick, F. Weik, and H. Wieman, Phys. Rev. Lett. **52**, 1590 (1984).
3. R. D. Renfordt, D. Schall, R. Bock, R. Brockmann, J. W. Harris, A. Sandoval, R. Stock, H. Strobele, D. Bangert, W. Rauch, G. Odyniec, H. G. Pugh, and L. S. Schroeder, Phys. Rev. Lett. **53**, 763 (1984).
4. R. Stock *et al.*, Phys. Rev. Lett. **49**, 1236 (1982); J. W. Harris *et al.*, Phys. Lett. B **153**, 377 (1985).
5. Y. Yariv and Z. Fraenkel, Phys. Rev. C **20**, 2227 (1979); C. Cugnon, D. Kinet, and J. Vandermeulen, Nucl. Phys. A **379**, 553 (1982); J. Cugnon and D. L'Hote, Phys. Lett. B **149**, 35 (1984).
6. H. Kruse, B. Jacak, and H. Stocker, Phys. Rev. Lett. **54**, 289 (1985); J. J. Molitoris and H. Stöcker, Phys. Rev. C **32**, 346 (1985).
7. P. Danielewicz and G. Odyniec, Phys. Lett. B **157**, 146 (1985).

Neutrino–Electron Scattering

The currently popular theories of fundamental forces are gauge theories. Within these theories, the gravitational, electromagnetic, and the strong and weak nuclear forces that operate between fermions are transmitted by the exchange of bosons. It is this basic similarity in the structure of the theories that tantalizingly suggests the existence of a single, unified description of the four forces. A significant advance has been made by the unification of the electromagnetic force and the weak nuclear force. This electroweak gauge theory of Weinberg, Salam, and Glashow (WSG) is characterized[1] by the interchange of four vector bosons—the photon, the charged W particles (W^+ and W^-), and the neutral Z^0. So far the weak interactions have been studied in reactions involving the exchange of W and Z bosons, and by the interference between the Z and photons. Now, in an experiment currently underway at the Los Alamos Meson Physics Facility (LAMPF), evidence is beginning to appear for Z^0–$W^\pm$ interference.

This next important test of the WSG theory is being studied in the context of the elastic scattering of electron–neutrinos by electrons $\nu_e e \rightarrow \nu_e e$. The $\nu_e e$ scattering proceeds through charged and neutral weak currents—the exchange of both $W^\pm$ and Z^0 bosons—and hence is sensitive to the interference between them; the WSG theory predicts about a 40% decrease in the total elastic cross section. Using an intense ν_e beam (with energies up to 53 MeV) from the LAMPF proton beam stop, a collaboration from the University of California at Irvine, Los Alamos, and the University of Maryland has made the first observation of $\nu_e e$ scattering.[2]

Neutrino–electron scattering events appear as single electron-recoil tracks in a 15-ton detector located near the beam stop. Events are expected to be concentrated in a 16-degree angular cone about the incident neutrino direction, and indeed the observed angular distribution shows a pronounced forward peak. The measured rate, even with the LAMPF accelerator producing a proton beam of up to 1 mA, is only about one event every two days. After six months of observation, the experimenters are reporting 51 ± 15 events for $\nu_e e$ scattering.[2] This result agrees with a prediction from the WSG theory of 53 ± 8 events. The experiment is continuing with the intent of substantially increasing the number of $\nu_e e$ events and thereby providing a definite statement about Z^0–$W^\pm$ interference.

R. L. Burman, Los Alamos National Laboratory and H. H. Chen, University of California at Irvine

1. S. Weinberg, Rev. Mod. Phys. **52**, 515 (1980); A. Salam, *ibid.* **52**, 525 (1980); S. L. Glashow, *ibid.* **52**, 539 (1980).
2. R. C. Allen *et al.*, Phys. Rev. Lett. (in press, 1985).

Anomalous Positron Peaks from Superheavy Collision Systems

On many occasions in the past, the ability to produce extreme conditions in the laboratory has provided unique information on the structure of matter. Such an opportunity is potentially created when heavy projectiles such as Th and U collide with Th, U, and Cm atoms at bombarding energies which can bring the collision partners into contact. For the short time that the two nuclei are close together, the combined nuclear charges may form the core of a quasiatom that simulates the atomic environment expected in a superheavy atom with an atomic number as large as 188. The feature of special interest drawing attention to such systems is the presence of extremely large electric field intensities which can bind the innermost *K*-shell electrons in the quasiatom with an energy larger than twice the electron's mass ($2mc^2$), allowing the testing of a fundamental tenet of quantum field theory that positrons can be spontaneously created from the vacuum in strong static external fields.[1]

More specifically, the source of the instability in the electron–positron vacuum can be viewed as a change of character in the bound state of the electron as it crosses the threshold of $2mc^2$ binding energy. In crossing this boundary the bound state develops into a resonance marking a decaying state and, thus the onset of the instability. Energy considerations show that if the K-shell states are unoccupied the vacuum rearranges to fill them by pair creation, spontaneously emitting the positrons of the pair. Thus a neutral vacuum (the bare nuclear charge is considered as a spectator) is predicted in quantum electrodynamics (QED) to "spark" in supercritical electric fields with the positrons carrying off kinetic energy equal in magnitude to the K-shell binding energy in excess of $2mc^2$.[1,2] The resulting charged vacuum is the new QED ground state in supercritical fields.

The possibility that this process has indeed been observed received some encouragement recently by the striking discovery[3-5] of narrow positron peaks emitted in supercritical collision systems at bombarding energies near the Coulomb barrier. It bears emphasis that the observation of these peaks provokes considerable interest on general grounds in addition to their possible connection to spontaneous positron emission, since the mere occurrence of such narrow, low energy positron structures is anomalous and speaks for an unorthodox explanation, possibly involving a previously undetected source. If these narrow peaks are indeed connected specifically to spontaneous positron emission, then there arises the interesting implication that some long-lived system is being formed and that this is the source of the supercritical field.

In this connection, Greiner and co-workers have demonstrated that the appearance of the positron peak in the U + Cm collision system, its energy, and its intensity can all be explained by proposing the formation of a giant, dinuclear, metastable system (with a lifetime about 10^{-19} sec) with total charge $Z_u = 188$ in a small fraction (0.1%) of the close collisions.[1] The mechanism for evolving this quasimolecular nuclear configuration involves the trapping of the collision partners in a pocket formed in the Coulomb potential by the nuclear forces. The positron line spectra may thus become a unique source of information on exotic nuclear species with masses considerably beyond any synthesized to date.

This proposal encounters difficulties, however, when the comparison with experiment is extended to include other collision systems. A particularly distinguishing signature of the model is the remarkable Z_u^{20} scaling of the energies of the peak for systems with similar nuclear charge distributions and states of ionization. This prediction has been tested[5] for a range of supercritical charges Z_u from 180 to 188. A near equality in the peak energies was observed, in contrast to the factor of 3 expected from the Z_u^{20} (Z raised to the 20th power) scaling. These results can only be accommodated in the spontaneous positron emission scenario in the unlikely case that radically different nuclear charge configurations and ionization states are assigned to the compound systems which track fortuitously with Z_u so as to maintain a constant K-shell binding energy.

The obvious question follows whether the peaks also appear in systems where supercritical binding is not expected. Exploring this question in Th + Ta with $Z_u = 163$, which is well below the spontaneous positron emission threshold of $Z_u = 173$ for normal nuclear density, one group has observed a peak with approximately the same characteristics as those found in the supercritical systems.[3,5] The present state of the analysis appears to indicate that a large fraction of the peak's intensity cannot be associated with a nuclear transition. If this conclusion persists under further scrutiny, this would effectively rule out spontaneous positron production as a possible source for all the peaks. Confronting the striking feature of a common peak energy, it has been speculated that the peaks may originate from the two-body decay of a previously undetected neutral particle produced in the collisions.[5] A clear signal for such a neutral particle would be provided by an accompanying monoenergetic electron from the $e^+ + e^-$ decay of the particle as well as a sharp total laboratory energy for the pair. Creation of charged pairs of particles is an alternate possibility to be considered. An experiment exploring both these speculations is presently in progress at GSI, Darmstadt, West Germany.

The discovery of the narrow positron lines, therefore, presents an interesting puzzle. Their mere occurrence is anomalous and suggests an unusual source. Resolving their origin is particularly provocative since it may have fundamental significance. The possibility that the production of the peaks may involve the strong electric and magnetic fields generated in the superheavy collision systems or the formation of giant nuclear complexes underscores the general interest in this puzzle involving the interplay of several fields of physics.

Jack S. Greenberg, Yale University

1. Theory Review: J. Reinhardt and W. Greiner, Experiment Review: J. S. Greenberg and P. Vincent, *Treatise on Heavy-Ion Science*, edited by D. A. Bromley (Plenum, New York, 1985), Vol. 5, pp. 1–421; Phys. Today **38**, 17 (November 1985).
2. J. S. Greenberg and W. Greiner, Phys. Today **35**, 24 (August 1982).
3. J. Schweppe *et al.*, Phys. Rev. Lett. **51**, 2261 (1983).
4. M. Clemente *et al.*, Phys. Lett. B **137**, 41 (1984).
5. T. Cowan *et al.*, Phys. Rev. Lett. **54**, 1761 (1985).

Some New Behavior at High Spins

In the last year or two several new ideas have emerged in high spin nuclear physics. This has occurred owing to the fortunate concurrence of a theoretical approach that is beginning to have some real predictive power and some very significant experimental advances. The current theoretical approach introduces Coriolis and centrifugal forces into the nuclear system by rotating ("cranking") a shell-model potential around one of its axes. Variation of the cranking frequency produces a range of states differing in angular momentum (spin) in much the same way as varying the Fermi level in the potential produces a range of nuclei differing in nucleon number. Experimentally high-spin physics is based on γ-ray spectroscopy and currently large arrays of high-resolution Compton-suppressed germanium detectors are being constructed around very compact low-resolution "balls" that detect essentially every one of the 20–30 γ-rays emitted in the deexcitation of a high spin state. This experimental development was pioneered at the Daresbury Laboratory in England, and makes studies possible around spin 40 in rare-earth nuclei, where several interesting changes in behavior occur. Three new ideas arising from these studies will be described here.

One of several important changes taking place in nuclei as the spin increases has to do with pairing. Pairs of similar nucleons tend to couple together in time-reversed orbits having a total spin of zero. Sometimes a number of these spin-zero pairs scatter from orbit to orbit in a coherent pattern called "pairing correlations," in close analogy to superconductors or superfluids. The nuclear "superfluidity" can be quenched not only by temperature, like the macroscopic analogs, but also by angular momentum, which requires a recoupling of the pairs to spin greater than zero. The nuclear pairing is fragile—based on only six or eight nucleons of each type—and cannot survive at high angular momenta. In the rotational region of rare-earth nuclei, the neutron pairing correlations are expected to be quenched by the time the spin reaches 40 and are experimentally observed to be mostly quenched. However, there is still an observed favoring of states where certain pairs of neutrons are coupled to spin zero over states with other couplings for these neutrons.[1] This indicates some remaining effects of the pairing and it has now been proposed[2] that the pairing correlations (which correspond to rotations in the gauge space) do not simply end, but rather turn over into pairing fluctuations (vibrations in the gauge space). These should be quenched also with increasing angular momentum, but more slowly, in better agreement with the experiment.

A basic question has to do with the way the nucleons are coupled to produce a given "high spin." The second new development sheds some light on this question for the case of a few nucleons outside a closed shell (valence nucleons). Calculation and experiment agree that a sufficient number of valence nucleons of each type (both protons and neutrons) favors a collectively rotating prolate nucleus, whereas an insufficient number tends to result in an oblate (or, at low spin, spherical) shape and a noncollective behavior, where the particle angular momenta are individually aligned. An interesting situation occurs at the boundary between these regions, where "terminating bands" can exist, in which the lower spins rotate collectively, but gradually the pressure for more angular momentum forces the valence nucleons to the noncollective oblate limit and the band ends. Such bands have been seen in light nuclei; the classic example being ^{20}Ne, where the band terminates at spin 8. Recent calculations first suggested that a similar behavior might be observable in much heavier nuclei.[3] The first reasonably clear experimental example is ^{156}Er, which was recently found[4] to be prolate and collective up to spin 30, beyond which an irregular, but apparently somewhat collective, sequence of levels continues up to a noncollective state at spin 42, very likely the predicted band termination with all ten valence nucleons fully aligned. In the nearby nucleus ^{158}Er, a similar sequence is seen terminating at spin 46 (all 12 valence nucleons aligned). How well the terminating-band picture describes these sequences remains to be seen, but at least the fully aligned terminating states seem to occur very much as calculated.

A third new idea is just being formulated, but has exciting implications. Most high-spin work to date has involved resolving individual γ rays, constructing level schemes from them, and interpreting these schemes. This procedure works for spins up to 30 or 40, where much of the "population" following a nuclear reaction "condenses" into the lowest few ("cold") states of each spin. At higher spins, however, the population is virtually all flowing through many rather highly excited ("hot") states where the overall level density is high. Individual γ rays from this region cannot be resolved, but their general properties can be studied, and it is known that they are mostly rotational-type transitions. Recent interest has thus centered on understanding what happens when a rotational band is superimposed on a high density of other levels, with which the individual band members must mix. One result just recognized[5] is that the normally strong correlations among γ-ray energies in a rotational sequence should be weaker—in striking agreement with some recent experimental observations.[6]

Much remains to be done before we know what is happening in these very high-spin cascades, but the possibility that a mixing of levels ("damping") plays a role seems likely right now. That one might learn about damping from high-spin studies was almost totally unexpected as little as a year ago.

F. S. Stephens, Lawrence Berkeley Laboratory

1. J. C. Bacelar *et al.*, Nucl. Phys. A (in press).
2. R. A. Broglia, M. Diebel, M. Gallardo, and S. Frauendorf (NBI preprint, 1985).
3. T. Bengtsson and I. Ragnarsson, Phys. Scr. **T5**, 165 (1983).
4. F. S. Stephens *et al.*, Phys. Rev. Lett. (to be published); P. Tjøm *et al.*, *ibid.* (submitted).
5. T. Døssing, Niels Bohr Centennial Symposium on Nuclear Structure, Copenhagen, May, 1985; B. Lauritzen, R. A. Broglia, and T. Døssing (unpublished results).
6. J. C. Bacelar *et al.*, Phys. Rev. Lett. (submitted); J. E. Draper *et al.*, *ibid.* (submitted).

OPTICS

Periodic and Chaotic Pulsations in Lasers

When the first solid state lasers became a reality in the early 1960's their typical mode of operation involved the emission of highly irregular bursts (spiking action). Over the last 25 years highly stable sources of light have become a common laboratory tool. Yet, there is conclusive evidence that under certain conditions stable laser action is impossible, even in principle; in fact, some lasers are known to break away spontaneously from the continuous-wave (cw) mode of operation and to develop regular or irregular output pulsations.

The underlying motivation for the current interest in laser instabilities is at least twofold; from a practical viewpoint, a detailed knowledge of the conditions that favor undamped pulsations is an important prerequisite for the development of new laser systems or scaled-up versions of existing devices. From a more fundamental viewpoint laser instabilities are the natural result of the nonlinear dynamics that govern innumerable other areas of science and technology.

One sign of the vitality of this field of research is the special issue of the Journal of the Optical Society of America devoted to laser instabilities; more than 30 original papers and review articles were assembled by an international panel of experts.[1] In addition, a well-attended conference on this subject was held at the University of Rochester under the joint sponsorship of the Institute of Optics, the NATO Advanced Research Program, and the Optical Society of America.[2]

One group of scientists has observed pulsing behavior[3] and bichromatic operation in multimode dye lasers and have identified many of the characteristic signatures of a certain instability predicted theoretically more than 15 years ago. New evidence from numerical studies of laser models shows that chaotic or pulsing solutions may coexist with stable solutions.[5] Thus, the experimental emergence of stable or unstable solutions may depend not only on the initial conditions, but also on the turn-on process and the history of the system.

A new type of laser instability, resulting in a transition from single-mode to multimode behavior, has been predicted and perhaps identified in CO_2 laser experiments.[6] This is a potentially important addition to the existing catalogue of unstable behavior because its low threshold makes it readily accessible to experiments, and because its characteristics appear to provide the ideal environment for the production of controlled output modulation.

C. O. Weiss and collaborators in Braunschweig, West Germany have achieved the unusually difficult experimental conditions necessary for single-mode instabilities (the so-called Lorenz–Haken instability[7]) in homogeneously broadened lasers, and have found evidence for periodic and chaotic pulsations in the output of a CO_2-pumped far infrared laser.[8] Although the Lorenz model was developed in the study of hydrodynamic convective instabilities, and has since been widely used as a theoretical paradigm, Weiss's laser work represents the first experimental observation of such behavior in an active laser medium. In fact, Weiss's studies, in parallel with recent theoretical investigations,[9] have been the source of a major surprise: the single-mode instability that was widely expected to emerge in association with a chaotic attractor can, in fact, display a wide range of regular periodic oscillations as well.

Irregular behavior has long been a common feature of experimental laser phenomenology. There is now growing evidence that numerous instances of irregular behavior are indeed a manifestation of deterministic chaos. New and powerful techniques have been developed to discriminate between dynamical chaos and ordinary noise. New experimental work has found fractal dimensionality from the strange attractor underlying chaotic laser emisssion.[10]

Carefully controlled experiments have been devised with externally modulated and driven lasers.[11] They have shown harmonic and subharmonic resonances, hysteretic behaviors, and a wealth of fine structure. When driven hard, these systems have all shown clear evidence of chaotic behavior with multiple coexisting basins of attraction.

N. B. Abraham, Bryn Mawr College;
L. A. Lugiato, University of Milan;
and L. M. Narducci, Drexel University

1. J. Opt. Soc. Am. B 2, January (1985), Special Issue on Instabilities in Active Optical Media.
2. *Proceedings of the International Conference on Instabilities and Dynamics of Lasers and Nonlinear Optical Systems*, edited by R. W. Boyd, M. G. Raymer, and L. M. Narducci (Cambridge University, Cambridge, to be published).
3. L. W. Hillman, J. Krasinski, R. W. Boyd, and C. R. Stroud, Jr., Phys. Rev. Lett. **52**, 1605 (1984); L. W. Hillman, J. Krasinski, K. Koch, and C. R. Stroud, Jr., J. Opt. Soc. Am. B **2**, 211 (1985).
4. H. Risken and K. Nummedal, J. Appl. Phys. **39**, 4662 (1968); R. Graham and H. Haken, Z. Phys. **213**, 420 (1968).
5. L. W. Casperson, J. Opt. Soc. Am. B (to be published).
6. L. M. Narducci, J. Tredicce, D. K. Bandy, L. A. Lugiato, and N. B. Abraham, Phys. Rev. A (to be publisbed).
7. E. N. Lorenz, J. Atmos. Sci. **20**, 130 (1963); H. Haken, Phys. Lett. A **53**, 77 (1975).
8. C. O. Weiss, W. Klische, and P. S. Ering, Opt. Commun. **52**, 405 (1985).
9. L. M. Narducci, H. Sadiky, L. A. Lugiato, and N. B. Abraham, Opt. Commun. (to be published).
10. A. M. Albano, J. Abounadi, T. H. Chyba, C. E. Searle, S. Yong, R. S. Gioggia, and N. B. Abraham, J. Opt. Soc. Am. B **2**, 47 (1985); G. P. Puccioni, A. Poggi, W. Gadomski, J. R. Tredicce, and F. T. Arecchi, Phys. Rev. Lett. **55**, 339 (1985).
11. W. Klische, M. R. Telle, and C. O. Weiss, Opt. Lett. **9**, 561 (1984).

Shortest Optical Pulses Produced by Pulse Compression

Since the development of the mode-locked laser, the ultimate temporal resolution for measurements of physical phenomena has been determined by laser pulsewidths. Therefore, as laser pulses have become shorter and shorter, it has become possible to initiate and observe faster and faster phenomena. Even though the realizable pulsewidths have decreased by orders of magnitude, they are still longer than many important physical processes. Consequently, each improvement in short-pulse laser technology immediately improves the time resolution of fundamental measurements.

Recent efforts to generate even shorter laser pulses have proceeded along two lines of development. One line has been to produce shorter mode-locked pulses directly from the laser source. The other has been to compress the output pulses from available lasers.

Laser-source development has led to the development of the colliding pulse, passively mode-locked, ring dye laser (CPM laser), which is capable of producing 55-fsec pulses (1 fsec $= 10^{-15}$ sec) at a 100-MHz repetition rate. Most recently developed is the compensated, or balanced, CPM laser, which produces 27-fsec pulses, also at 100 MHz.

Optical-pulse compression has led to even shorter pulses. The optical-pulse compression schemes are based on the idea originally developed for chirp radar, whereby a frequency-swept pulse is sent through a dispersive delay line. In simple terms, the group velocity of the light is determined by its instantaneous frequency so that different frequency components of the pulse travel at different speeds through the delay line. The length of the line is adjusted so that the leading edge of the pulse is delayed by just the right amount to overlap the trailing edge at the output of the delay line. Under optimal conditions, the output pulsewidth is given by the reciprocal of the bandwidth of the frequency sweep.

The use of this scheme requires a method for producing a linearly frequency-swept (chirped) optical pulse and an optical delay line with sufficient dispersion to compress the frequency-swept pulse. For optical pulses with picosecond pulsewidths and less (1 psec $= 10^{-12}$ sec) it is quite difficult using electro-optic techniques, to obtain the required magnitude of frequency sweep. However, by propagating an intense short pulse through a single-mode optical fiber, the frequency becomes swept and the frequency bandwidth broadened. The combination of the nonlinear as well as the linear interactions between the light pulse and the optical fiber results in an output pulse that is nearly ideal for subsequent compression by a dispersive delay line. This situation is a key feature of the optical-fiber pulse compressor,[1] which has by now been used at many laboratories and with many different laser systems to compress pulses by orders of magnitude. Recently, a commercial version of the compressor has become available.

Since 1982, the shortest pulses have been obtained by compressing CPM-laser pulses with the optical-fiber pulse compressor. The first application of this powerful combination was performed by Shank *et al.*,[2] who compressed 90-fsec, amplified, CPM laser pulses to 30 fsec at a 10-Hz repetition rate. Two years later, Fujimoto *et al.*[3] compressed 60-fsec amplified CPM laser pulses to 16 fsec at the same 10-Hz repetition rate. We then compressed 110-fsec, amplified, CPM-laser pulses to 12 fsec at an 800-Hz repetition rate.[4] Most recently, Knox *et al.* compressed 40-fsec amplified compensated CPM laser pulses to 8 fsec, or only four optical cycles, at a 5-kHz repetition rate.[5]

The nontunability of the CPM laser limits the utility of the above compressed pulses for the study of time-dependent resonant processes in atomic, molecular, and condensed-matter systems. To surmount this problem of generating frequency-tunable, ultrashort pulses, our latest effort has been directed at further compression of frequency-tunable, mode-locked, dye-laser pulses. Recently, by using two stages of pulse compression, where the output pulses from the first stage were amplified before entering a second optical-fiber pulse compressor, we obtained 16-fsec pulses at a 200-Hz repetition rate.[6] These pulses had peak powers of 80 kW and were tunable over the wavelength range of the dye laser. This method can be applied to mode-locked lasers operating at any wavelength.

Daniel Grischkowsky, IBM T. J. Watson Research Center

1. H. Nakatsuka, D. Grischkowsky, and A. C. Balant, Phys. Rev. Lett. 7, 910 (1981); D. Grischkowsky and A. C. Balant, Appl. Phys. Lett. **41**, 1 (1982); D. Nikolaus and D. Grischkowsky, *ibid.* **43**, 228 (1983).
2. C. V. Shank, R. L. Fork, R. Yen, R. H. Stolen, and W. J. Tomlinson, Appl. Phys. Lett. **40**, 761 (1982).
3. J. G. Fujimoto, A. M. Weiner, and E. P. Ippen, Appl. Phys. Lett. **44**, 832 (1984).

4. J.-M. Halbout and D. Grischkowsky, Appl. Phys. Lett. **45**, 1281 (1984).
5. W. H. Knox, R. L. Fork, M. C. Downer, R. H. Stolen, C. V. Shank, and J. A. Valdmanis, Appl. Phys. Lett. a**46**, 1120 (1985).
6. S. L. Palfrey and D. Grischkowsky, Opt. Lett. (to be published).

Low Chirp VPT-Distributed Feedback Lasers

In optical fiber transmission systems using pulsed semiconductor lasers, small frequency shifts occur during pulse modulation even in single longitudinal mode semiconductor lasers. This dynamic frequency shift, known as "chirp" (from a radar analogy) can lead to catastrophic dispersion problems in very high bit rate applications.

Using a new vapor phase transport (VPT) fabrication process for crystal growth with unusual geometries, 1.55 μm wavelength distributed feedback semiconductor lasers have been produced which display extremely stable lasing frequencies even under 4 Gbit/sec (4×10^9 bits/sec) direct modulation.[1,2]

In a distributed feedback laser the cleaved-facet mirror resonator of a conventional semiconductor laser is replaced with a diffraction grating actually buried inside the crystal along the length of the laser cavity (see Fig. 1). In such a structure the light is continuously folded back on itself since the grating provides a wavelength selective reflection mechanism. Thus no mirrors are needed and only one frequency will resonate in a design with a properly phased grating.

While a single frequency resonator is essential for direct modulation in dispersive fiber transmission, even this is insufficient. Small changes in the index of refraction which occur during modulation constantly retune the resonator for a slightly different frequency, thus leading to chirping. Both theoretical work and time-resolved spectral measurements have revealed that the most deleterious frequency shifts occur during the turn-on transients of the digital optical pulse when the light "rings" or oscillates before settling down to its desired value.[3,4] While these wavelength shifts may be less than 1 Å, they still cause problems at high enough bit rates. Dispersion causes the different frequency components of the optical pulse to travel at different velocities in the fiber, and portions of a pulse can overlap into the neighboring time slot. Theory and experiment together suggest that this effect is minimized by a nonlinear damping in the laser gain medium if the light has a very high intensity inside the laser.

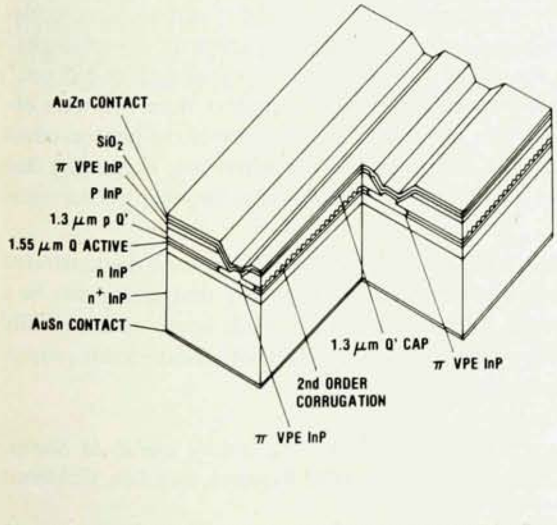

FIG. 1. A cut-away view of the Vapor Phase Transported Distributed Feedback (VPT-DFB) laser showing the buried diffraction grating and the various layers of semiconductor crystal growth.

Owing to the unusual capabilities of the VPT fabrication process, it is easy to make optical cavities which confine the optical power to small dimensions, thus increasing the optical intensity. Under the proper conditions, the vapor phase crystal growth will occur even down inside the deep, thin, etched grooves along the sides of the laser, which define a narrow optical waveguide. The result is a laser which suppresses the ringing and frequency chirp that occur during pulse transients.

The low chirping largely eliminates dispersion problems and has permitted the VPT-distributed feedback laser to establish two record transmission results for directly modulated lasers over optical fiber, the most recent being the error-free transmission of 4 Gbit/sec data over 103 km of optical fiber with no repeaters.[2] This work has led to a deeper understanding of dispersion problems in very high bit rate systems. It also could influence future coherent-detection systems where information may be encoded in the small frequency shifts themselves rather than pulses in the optical power.

T. L. Koch, AT&T Bell Laboratories, Holmdel, New Jersey

1. T. L. Koch, *et al.*, Appl. Phys. Lett. **47**, 12 (1985).
2. A. H. Gnauck, *et al.*, paper PD-2 at 1985 Optical Fiber Communications Conference, San Diego, CA.
3. T. L. Koch and J. E. Bowers, Electron. Lett. **20**, 1038 (1984).
4. R. A. Linke, IEEE J. Quantum Electron. **QE-21**, 593 (1985).

Shaping of Ultrafast Optical Pulses

A new technique has been invented for producing arbitrarily shaped, high-speed optical pulses. This achievement can have an important impact on such diverse fields as optical digital communications and laser fusion. The pulse shaping is produced by first passing an optical pulse (only picoseconds long) through a short length of optical fiber to cause the color (wavelength and optical frequency) of the light to change during the pulse. This "frequency chirped" pulse is then passed through a specifically designed optical time delay apparatus in which the amplitude and delay of each color in the pulse is individually controlled. When the light emerges, an optical pulse with the desired shape is obtained.

If you wish to produce a specially shaped electrical pulse, it is often possible to simply purchase a pulse generator which can produce the desired pulse shape. This is not true of optical pulses. Recent advances in high speed laser technology have made it possible to obtain optical pulses whose time durations are as short as 8 fsec. Such short pulses offer tremendous opportunities for studies of physical processes in experiments which give essentially stop-action photographs. Until now the precise shape of the pulses was not controllable. The new technique, invented by scientists at Bell Communications Research, allows the pulse shape to be controlled even on this incredibly short time scale.

Potential applications of specially shaped pulses are diverse. In the first experiments the technique was used to "clean up" a picosecond pulse.[1] Such pulses are plagued by a low intensity but extremely wide time width background. As much as 50% or more of the power may be found in the background. The pulses are in fact perhaps better described as a long optical pulse with a picosecond feature on the pulse. The Bellcore scientists were able to use their technique to completely eliminate the background.

In subsequent experiments they were able to demonstrate the formation of pulse sequences and most recently the creation of a "square" optical pulse.[2] Such optical pulses can have important uses in experiments which are designed to reveal and control the properties of materials that are important to telecommunications devices. The new technique may also make possible the design of special optical pulses or coded pulse sequences which could improve fiber optic communication systems. Laser fusion systems would also benefit from the ability to produce a properly shaped optical laser pulse. The potential for making specially coded pulse sequences on this time scale can prove important to improved performance of optical radar systems. Studies are underway to explore the new opportunities opened by the availability of shaped pulses.

Paul Liao, Bell Communications Research, Holmdel, New Jersey

1. J. P. Heritage, R. N. Thurston, W. J. Tomlinson, A. M. Weiner, and R. H. Stolen, Appl. Phys. Lett. **45**, 87 (1985).
2. J. P. Heritage, A. M. Weiner, and R. N. Thurston (submitted for publication).

Photon-Gated Spectral Hole Burning

Persistent spectral hole burning (PHB) is a frequency-selective bleaching phenomenon that provides a new dimension for optical storage of information (see *Physics News in 1982*, p. 69). In the most general form of PHB, narrow depressions or "holes" are formed ("burned") in an inhomogeneously broadened absorption line of an absorber in a solid at low temperatures whenever light absorption causes a change in the absorbing center. At low temperatures the holes can be stable for years; however, by irradiation at appropriate wavelengths the holes can also be erased. The frequencies or wavelengths at which holes have been burned serve as an additional dimension for the storage of digital information.[1] Since typical ratios of the inhomogeneous bandwidth to the holewidth are in the range 10^3 to 10^4, as many as 1000 bits or more of information can be stored in one laser focal volume, leading to areal densities that may be as large as $10^{11}/cm^2$. To make such an idea practical, materials with specific PHB properties must be discovered and understood.

Mechanisms giving rise to PHB can be photochemical or photophysical, and the effect has been observed for ions, molecules, and color centers in crystalline and amorphous hosts.[2] For each material, the techniques of laser spectroscopy of solids can be used to measure holewidths, relaxation times, quantum efficiencies, and other basic microscopic properties of the physical system. Essentially all of the mechanisms studied until recently have been single-photon mechanisms; that is, the photoinduced change leading to hole burning (writing) for a given center occurs with a fixed probability after the absorption of one photon. Such linear, monophotonic processes suffer from the drawback that the act of detecting holes (reading) also produces changes in the absorption line. Recent modeling studies of the generalized single-photon process have shown that thousands or tens of thousands of reads can be obtained from single-photon mechanisms only when the material possesses high quantum efficiency and low absorption cross section.[3] These restrictive requirements do not apply for photon-gated hole-burning mechanisms, that is, those mechanisms for which hole burning occurs only in the presence of an additional "gating" light source, because for these mechanisms, reading is performed in the absence of the gating light and is therefore nondestructive.

Recently, two-color, photon-gated spectral hole burning was observed for the first time in an inorganic material, $BaClF:Sm^{2+}$, and subsequently also in an organic material, carbazole in boric acid glass, demonstrating that nondestructive reading of spectral holes is possible. In the inorganic material photoionization of Sm^{2+} occurs, and a gating enhancement factor of 10^4 was readily observed.[4] A remarkable and novel feature of this material is that holes can be recovered after temperature cycling to 300 K.

In the organic material composed of carbazole molecules in boric acid glass, the first photon excites the lowest singlet–singlet transition of carbazole at a wavelength of 335 nm.[5] Gating enhancement factors of greater than 500 were observed for this material. The spectrum of the photoproduct parallels that of the carbazole positive ion, suggesting that the mechanism for gated PHB is also two-step photoionization.

In summary, photon-gated PHB has been demonstrated in two classes of materials, indicating that gating may be a widespread phenomenon. This result opens up a radically new class of mechanisms for PHB with the desirable property of nondestructive reading.

W. E. Moerner, R. M. Macfarlane, and R. M. Shelby, IBM Research, San Jose, California

1. G. Castro, D. Haarer, R. M. Macfarlane, and H. P. Trommsdorff, "Frequency selective optical data storage system," U.S. Patent No. 4,101,976

(1978); W. E. Moerner, Photonics Spectra, February 1985, p. 59.

2. W. E. Moerner, J. Mol. Electron (in press, 1985), and references therein.
3. W. E. Moerner and M. D. Levenson, J. Opt. Soc. Am. B **2**, 915 (1985).
4. A. Winnacker, R. M. Shelby, and R. M. Macfarlane, Opt. Lett. **10**, 350 (1985).
5. H. W. H. Lee, M. Gehrtz, E. Marinero, and W. E. Moerner, Chem. Phys. Lett. **118**, 611 (1985).

Array of Picosecond GaAs Optical Gates

Application of light in signal processing, communication, and number crunching has attracted considerable attention in recent years. The possibility of taking advantage of the parallelism of light and its massive interconnection capability is very exciting. Nonlinear optical bistable switches and gates promise logic operations necessary for high speed optical computing. But before optical bistable devices integrate into a working computer or signal processor, the switching times have to be reduced and a large array of devices has to be demonstrated. Advances in both of these areas have been reported during the past year.

Various optical logic operations such as AND, OR, NAND, and XOR were performed in a nonlinear GaAs Fabry–Perot etalon at room temperature by a University of Arizona/AT&T Bell Laboratories collaboration.[1] In optical gates, the transmission of a low intensity "probe" beam (gate output) is modified by the application of one or two "control" beams (inputs to the gate). The optical gate or the bistable switch is a nonlinear medium sandwiched between two partially reflecting mirrors, forming a nonlinear Fabry–Perot etalon. For GaAs devices, the nonlinearity is obtained by "saturating" the room-temperature exciton resonance by "control" beams, thereby changing the index of refraction of the medium at the probe wavelength.

The demonstration of a 1-psec (10^{-12} sec) response time of a GaAs optical NOR gate was reported by researchers at the University of Arizona, Ecole Polytechnique, and Ecole Normale Superieure.[2] Short pulses of 100-fsec (10^{-13} sec) duration were employed to show that the transmission state of the NOR gate changes from HIGH to LOW in about 1 psec, corresponding to the switch-on time of a bistable device. Thus a logic decision can be obtained in about 1 psec, but the repetition rate for the gating operation depends on the carrier recombination time which is usually a few tens of nanoseconds. This relaxation time has recently been reduced to less than 200 psec by proton bombarding the material[3] and also by enhancing surface recombination[4] by eliminating the top window of the crystal grown by molecular beam epitaxy (at Caltech). A collaboration of groups at the University of Arizona, Caltech, and Bell Communications Research reported a recovery time of less than 200 psec for GaAs gates.[4] The 1-psec switch-on time and 200-psec recovery time are the fastest reported for such low energy, nonlinear optical devices.

The fabrication of a large array of GaAs optical devices was also reported by the same collaboration.[5] The array consisted of over 100×100 elements, each element having a size of $9 \times 9\ \mu m^2$. The pixels were defined by using a freon, helium, and oxygen gas mixture to etch a GaAs crystal grown on top of an AlGaAs window. Then the array was sandwiched between two 94% reflectors, forming the two-dimensional nonlinear etalons. The gating operation on one individual pixel of the array was examined, and a fast recovery time was established. Parallel operations of this small 100×100 array at the reported rate of about 10 GHz should result in processing rates of 10^{14} sec^{-1}. Larger arrays of 1000×1000 are relatively easy to fabricate and therefore higher rates are possible. Thermal, cascade, and parallel architecture problems are now being attacked.

N. Peyghambarian and H. M. Gibbs,
Optical Circuitry Cooperative and Optical Sciences Center,
University of Arizona

1. J. L. Jewell, Y. H. Lee, M. Warren, H. M. Gibbs, N. Peyghambarian, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **46**, 918 (1985).
2. A. Migus, *et al.*, Appl. Phys. Lett. **46**, 70 (1985); N. Peyghambarian *et al.*, Proceedings of the Picosecond Electronics and Optoelectronics, March 13–15, 1985, Lake Tahoe, Nevada.
3. Y. Silberberg, P. W. Smith, D. A. B. Miller, B. Tell, A. C. Gossard, and W. Wiegmann, Ref. 2; Appl. Phys. Lett. **46**, 701 (1985).
4. Y. H. Lee, W. Warren, G. R. Olbright, H. M. Gibbs, N. Peyghambarian, T. Venkatesan, J. S. Smith, and A. Yariv, Opt. Lett. (submitted).
5. T. Venkatesan *et al.*, Appl. Phys. Lett. (submitted).

PLASMA AND FUSION PHYSICS

The study of plasma physics is concerned with the behavior of gases that consist primarily of charged particles. The only naturally occurring plasmas exist in the ionosphere, in outer space, and in the environment of various astrophysical objects. These are studied directly and indirectly by using satellites and telescopes. Such plasmas are not readily accessible and are almost never susceptible to any control. Extensive efforts are therefore devoted in plasma physics to the production, heating, confinement, and study of laboratory plasmas. Research during 1985 included the launching of sophisticated satellites that injected artificially produced plasma into the solar wind. Fusion experiments were continued in many laboratories throughout the world. This research is focused on the ultimate goal of igniting and burning deuterium–tritium plasmas at temperatures of 100 million degrees and higher. The experiments involve magnetic confinement of relatively large volumes of plasma or the inertial confinement of very dense pellet plasmas. The richness of fundamental plasma physics is illustrated by the recent observation of magnetic helicity conservation in some plasma confinement experiments. Fundamental advances have also occurred in understanding pure electron or pure ion, unneutralized laboratory plasmas. All of these developments are described briefly in this review.

Harry Dreicer, Los Alamos National Laboratory

Space Plasma Physics 1985

Remarkable achievements in space plasma physics research are being obtained in experiments and observations made by a group of satellites in the AMPTE (Active Magnetospheric Particle Tracer Explorers) project. The group consists of three satellites, the IRM (Ion Release Module, provided by the Federal Republic of Germany, principle investigator: G. Haerendel), the subsatellite UKS (the United Kingdom Satellite, provided by England, leader: D. A. Bryant), and the CCE (the Charge Composition Explorer, provided by the USA, principal investigator: S. M. Krimigis).

The experiment is designed to inject rare earth ions (Li, Ba, and Eu) into the solar wind and the Earth's magnetosphere (the role of IRM) in order (a) to study local interactions of the artificially produced plasma and the ambient natural plasma (the role of IRM and UKS), (b) to study long range mass transport into and through the magnetosphere (the combined role of IRM and CCE), and (c) to make systematic exploration of the temporal variation at a wide energy range of the charge composition of natural plasmas (the role of CCE).

The three satellites were launched as a stack on August 16, 1984. IRM and UKS were placed in the same highly elliptical orbit with an apogee of 18.7 earth radii and a perigee of 550 km while CCE was placed in a near equational orbit having a perigee of 1108 km and an apogee of 8.8 earth radii.

Lithium ion releases were carried out in the solar wind on September 11 and 20 and a barium ion release on December 27, 1984. In each case, a diamagnetic cavity was created in the solar wind with the magnetic field at the IRM falling below the measurable level[1] (which is a factor of about 10^3 below the solar wind field). At the expanding boundary of the cavity, electron and ion heating, enhanced plasma waves, and amplification of the local magnetic field were observed.[1] The heating processes were found to have a striking similarity to those observed at the Earth's collisionless bow shock.

In the lithium releases, direct measurements of the acceleration of the newly created lithium ions by the solar wind electric field were made by both the IRM and UKS.[1] Ground-based optical observations showed in detail the creation of a barium ion "comet tail" from the injected ion coma and the evolution of an artificial comet over a period of about 5 min (see Fig. 1). The released ions, however, were not detected by CCE as originally planned. This indicates existence of unexpected processes which deviate the path of the particle transfer.

In addition to the active experiments, the project brought about many interesting observations of the natural plasma environment. For example, in the outer magnetosphere both IRM and CCE have observed for the first time energetic molecular ions (possibly O_2^+ or NO^+). In the interplan-

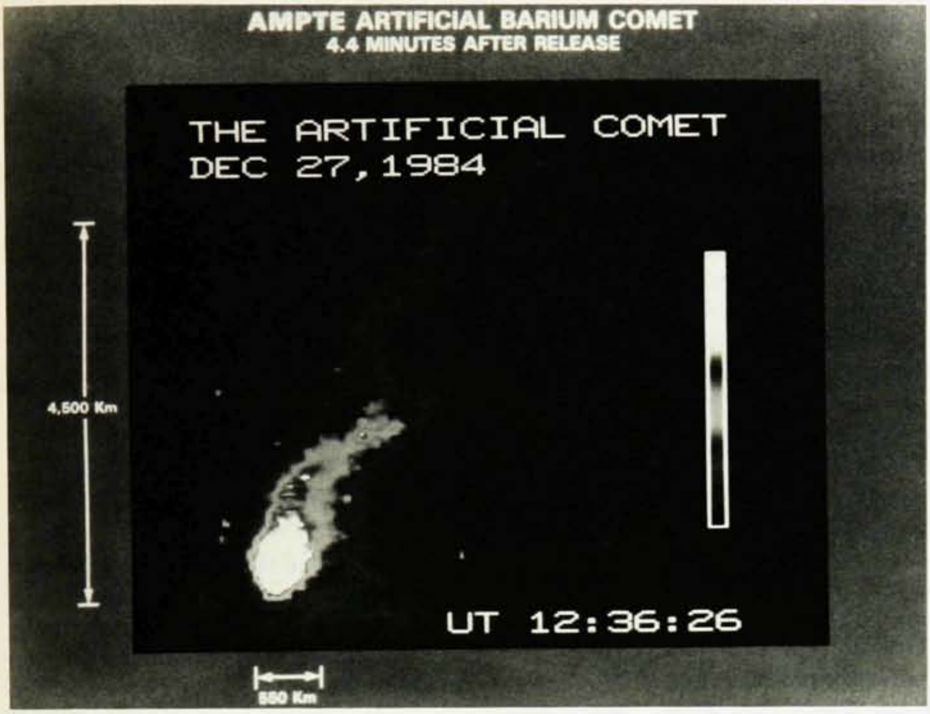

FIG. 1. Ground observation of the release of barium from the IRM satellite, creating, in effect, an artificial comet.

etary space the IRM has observed locally ionized helium which is considered to be of interstellar origin. Coordinated observations from the IRM and UKS have revealed magnetic and plasma structures at the magnetopause which are smaller than previously expected. The UKS, because of the high time resolution of the magnetic field and plasma wave data, has revealed unusually small scale (smaller than 15,000 km) current sheets in the solar wind which contain very hot plasmas with turbulent magnetic fields.

Within the magnetosphere, the CCE measured for the first time the mass and charge-state distribution of ions in the ring current (trapped low energy plasma in the Earth's magnetic field) over the energy range of 20 to 300 keV.[2] The CCE observed all charge states of oxygen (O^{+}–O^{7+}), carbon (C^{+}–C^{6+}), and helium ($He^{+,++}$), and studies of the relative variations of these throughout the magnetosphere are ongoing.[3]

Trapped energetic heavy ions have also been observed for the first time by CCE throughout the magnetosphere. Iron nuclei and nuclei of the silicon group (Na, Mg, Si), which are presumably accelerated within the magnetosphere but which are of solar origin can actually dominate all other species in the outer magnetosphere and at energies above 1 MeV. Remarkably extended power-law energy spectra of ions over eight orders of magnitude are a combination of H^{+}, He, CNO, Si, and Fe, and present evidence of the theoretical predicted distribution.[4]

I would like to thank G. Haerendel, S. M. Krimigis, and R. W. McEntire for their cooperation in preparing this manuscript.

Akira Hasegawa, AT&T Bell Laboratories, Murray Hill, NJ

1. Session on Active Magnetospheric Particle Tracer Experiment, AGU Spring Meeting 1985. EOS **66**, 350 (1985).
2. S. M. Krimigis, G. Gloeckler, R. W. McEntire, T. A. Potemra, F. L. Scarf, and E. G. Shelley, Geophys. Res. Lett. **12**, 329 (1985).
3. G. Gloeckler, B. Wilken, W. Stiidemann, F. M. Ipavich, D. Hovestadt, D. C. Hamilton, and G. Kremser, Geophys. Res. Lett. **12**, 325 (1985).
4. A. Hasegawa, K. Mima, and M. Duong-van, Phys. Rev. Lett. **54**, 2608 (1985).

Ohmic Heating Phase of TFTR

Since December 1982 the research program of the Tokamak Fusion Test Reactor (TFTR) at Princeton has alternated between experiments that optimized plasma conditions and studies of plasma confinement, and periods when the tokamak capabilities were upgraded. The objective of TFTR is to achieve and study plasmas at fusion reactor-relevant parameters—an ion temperature T_i of about 10 keV (10^8 K), and an average electron density $\bar{n}_e$ of 10^{20} m^{-3} to produce energy breakeven conditions in deuterium–tritium plasmas. To achieve this TFTR will supplement its ohmic heating with 27 MW of deuterium neutral beam heating. Low power (less than 6.5 MW) neutral beam injection experiments have been in progress since the summer of 1984 in parallel with the experiments directed toward the optimization and understanding of ohmically heated plasmas.[1]

An important feature of the tokamak is the large current (greater than 10^6 A) induced along the toroidal direction that ohmically heats the plasma, owing to its finite resistivity, to the 1–5 keV range and gives rise to a poloidal magnetic field. Presently, TFTR operates at currents near 2.5×10^6 Å, toroidal magnetic fields of 5.2 T (52 kG), and plasma durations of less than 6 sec. The electrons are ohmically heated directly by the induced current while the ions are heated through Coulomb collisions with the electrons. TFTR has obtained central electron temperatures of approximately 3–5 keV, central ion temperatures of 2.0–2.8 keV, and central electron densities of $7.5\text{–}16.0\times10^{19}$ m^{-3}. The energy confinement time (τ_E) of the plasma is defined as the total energy of the electrons and ions divided by the ohmic input power. In TFTR, the longest confinement time observed for the ohmic heating phase was 0.44 sec.

In tokamaks as well as other plasma confinement devices, impurities (that is, oxygen, carbon, and vacuum vessel metals) are an obstacle to producing high plasma densities and temperatures. From 1983 through the summer of 1984, TFTR operated with deuterium ion densities about 0.3–0.6 of the electron density owing to the abundance of multiply ionized carbon and oxygen. Impurity line radiation at the plasma edge accounted for 70%–100% of the total input power. Since then a program of prolonged experimentation and impurity reduction techniques has reduced the oxygen and carbon densities substantially. The ion density is now about 0.6–0.95 of the electron density, and the radiated power is as low as 25% of the input power.

Experimentally, the plasma heat loss in a tokamak is dominated by the electron's thermal transport, which is not clearly understood, while the ion transport is approximately predicted by models based upon collisions between charged particles on different magnetic orbits. Experiments have been conducted to determine the dependence of transport on macroscopic parameters. In TFTR, the confinement time is proportional to the electron density, the minor radius and the square of the major radius of the torodial plasma, and to the magnetohydrodynamic safety factor.[1] This relationship is similar to that seen on the Alcator C tokamak at MIT and is consistent with the trend in size observed by comparing the results from many tokamaks. There are, however, two recent TFTR experiments that deviate from this parametric trend: high density helium plasmas and high density plasmas fueled with solid deuterium pellets. In both experiments an electron density of 8×10^{19} m^{-3} was achieved, but the confinement time no longer improved linearly with density. For the case of the injected pellet fueled plasmas, a Lawson parameter of 6.8×10^{19} sec/m^3 was obtained. In the next two years high-powered neutral beam injection will be used to further heat the already ohmically heated plasmas in TFTR to reactor relevant conditions.

P. C. Efthimion, Princeton University

1. R. J. Hawryluk *et al.*, in *Heating in Toroidal Plasmas* (International School of Plasma Physics and ENEA, Varenna, 1984), Vol. II, p. 1012; P. C. Efthimion *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research 1984* (IAEA, Vienna, 1985), Vol. I, p. 29.

Magnetic Mirror Physics

Magnetic mirrors are plasma confinement devices that use open magnetic configurations and tend to have large axial plasma losses, parallel to the magnetic field. The recent history of magnetic mirror research has concentrated on the tandem mirror concept. This system consists of a central solenoid cell bounded by magnetic mirror end cells. It was developed to reduce (plug) the axial plasma losses by adding electrostatic potential barriers. Early tandem mirrors achieved an end cell ion plugging potential by increasing end cell density. The thermal barrier concept was invented to further improve axial ion plugging.[1] The basic idea is to insulate the central cell from end cell electrons by using an additional electron potential barrier (that is, a potential dip) so that the end cell electrons can be efficiently heated to increase the end cell plugging potential. Thermal barriers eliminate the need for large end cell densities.

The most important result in tandem mirror physics in the last year has been the demonstration of the basic physics of the thermal barrier concept on two different devices, the TMX-U at Lawrence Livermore National Laboratory (LLNL)[2] and Gamma-10 at the University of Tsukuba in Japan. Scientists working on TMX-U and Gamma-10 have now directly demonstrated all of the components of the thermal barrier: the potential dip, the ion plugging potential associated with a measured increase in plug electron temperature, increased central cell density associated with ion plugging, and the presence of magnetically trapped ions and electrons used to create the thermal barrier. Central cell density has continued to improve throughout the year and is now as high as 4×10^{12} cm^{-3} on Gamma-10.

Recent results[3] from Gamma-10 suggest that improved axisymmetry can reduce the radial transport of current across the magnetic field, which is characterized by a "perpendicular confinement time." In TMX-U the thermal barriers are located in end cells which have quadrupole magnetic symmetry while in Gamma-10 they are located in axisymmetric end cells and overall the device is more axisymmetric. The observed perpendicular confinement time for Gamma-10 falls off less rapidly than for TMX-U. This information is extremely encouraging because it indicates that other tandem mirror devices, such as TARA at MIT, which incorporate more axisymmetry, are likely to have even better perpendicular confinement as the electron confining potential is increased.

The understanding of macroscopic plasma stabilization produced by application of electromagnetic waves near the ion cyclotron resonance frequency (ICRF) is another area in which significant progress has been made. This technique promises the possibility of stabilizing purely axisymmetric tandem mirrors as reactor-relevant plasma parameters are achieved. Previously Phaedrus[4] at the University of Wisconsin and HIEI at Kyoto University[5] produced data demonstrating that ICRF could provide stability. During the last year, groups at LLNL, UC-Berkeley, and Science Applications International Corporation[6] have provided additions to the theory of ICRF stabilization which show that a wide variety of mechanisms could be present. Determining the relative importance of these will be the subject of future research.

Noah Hershkowitz, University of Wisconsin

1. D. E. Baldwin and B. G. Logan, Phys. Rev. Lett. **43**, 1318 (1979).
2. E. B. Hooper *et al.*, LLNL Report UCRL-92493 (1985).
3. M. Inutaki *et al.*, Phys. Rev. Lett. **55**, 939 (1985).
4. J. R. Ferron *et al.*, Phys. Rev. Lett. **51**, 1955 (1983).
5. Y. Yasaka and R. Itatani, Nucl. Fusion **24**, 445 (1984).
6. D. A. D'Ippolito and J. R. Myra, Phys. Fluids **28**, 1985 (1985).

Inertial Confinement Fusion (ICF)

The objective of the inertial fusion program in the near term (by 1990) is to demonstrate the feasibility of burning very small masses of thermonuclear fuel using lasers or particle beams. In the long term, the emphasis will be to develop inertial fusion as a source of commercial power production.

The basic concept of inertial fusion is that of implosion, drive by ablation, of a capsule containing thermonuclear fuel. There are two principal approaches to ICF: direct and indirect drive. In the indirect-drive approach, the driver beam energy is absorbed by a radiation case that converts the driver beam energy into x rays which then implode the target. In the direct-drive approach, a short-wavelength, high-intensity laser pulse is focused directly onto the thermonuclear capsule, ablating the outer layers which causes the target to implode.

In order to produce net energy gain, eventually leading to commercial power, the ICF program must develop a high-efficiency driver and achieve efficient energy coupling to the target, as well as high ablation pressure (greater than 50 Mbar) with low fuel preheat and ultrahigh compressed fuel densities (greater than 200 g/cm^3).

A number of different approaches to inertial fusion have been investigated in the last 15 years, including charged particle beams, long wavelength lasers, and short wavelength lasers.[1] This past year advances have been made in driver development, in understanding coronal physics processes, and in high-density compression physics.

In driver development, experiments with the Particle Beam Fusion Accelerator I (PBFA I) and Proto I at Sandia indicate that PBFA II, presently in the final phases of construction, could be an effective target driver, with projected incident intensities in excess of 10^{14} W/cm^2. The main difficulty experienced to date with light ions has been the inability to focus with high power beam. The 1984–1985 experiments at Sandia and in Japan[2] have resulted in success; research in the next few years will be directed towards achieving irradiance levels required to begin ignition experiments in the post-1987 years.

Other progress in driver development in 1985 includes the completion of NOVA at Livermore. The NOVA laser system is presently operational, delivering 50 to 70 kJ of energy at a wavelength of 1.054 μm, and approximately half of this energy at 0.53 and 0.35 μm.[3] The OMEGA glass laser system at the University of Rochester was fully converted to 0.35 μm operation in February.[4] OMEGA is currently capable of 2.4 kJ operation at 0.35 μm. Los Alamos terminated Antares operations at 10.6 μm for fusion experiments, and successfully demonstrated a prototype KrF amplifier module at 0.25 μm at an energy in excess of 10 kJ with an overall efficiency of 1.5%.[5]

Demonstrable progress has been made in confirming the predictions of the advantages of short-wavelength laser target irradiation in the plasma corona at fusion-relevant intensity-length products. Experiments have revealed the following features: an absence of hot electrons generated by resonance absorption at 0.35 μm; evidence that very energetic electrons (greater than 20 keV) are generated by the two-plasmon decay instability in direct-drive experiments at intensities greater than 10^{14} W/cm^2, but in negligible amounts (less than 0.1%)[6]; the first direct evidence that the Raman instability (another potential source of suprathermal electrons which can produce, preheat, and degrade a laser-driven implosion) is collisionally damped for near-reactor-size intensity-scale length products[7]; and high efficiency for the conversion of absorbed laser light to x rays (50% to 60%) at intensities of interest (10^{14} W/cm^2) on high-Z targets.[8] In experiments conducted to establish induced spatial incoherence as an alternative approach to achieving high uniformity of irradiation in direct-drive geometries, NRL investigators have observed increased suprathermal electron generation for laser-matter experiments with 1.054-μm light.[9] Experiments to be conducted with the newly completed Pharos III laser (1 kJ) at NRL will investigate the effects of finite bandwidth on plasma instabilities using 0.53 μm light.

Progress in high-density compression physics was highlighted by the attainment of compressed DT fuel densities of approximately 24 g/cm^3 (120 times solid density) in indirect, x-ray driven, implosion experiments at Livermore.[10] Direct-drive ablative implosion experiments conducted at Rochester have demonstrated thermonuclear neutron yields in excess of 2.0×10^{11} which will be useful in the development of various high-density diagnostic techniques for future inertial fusion experiments.[11] Measurements of the Rayleigh–Taylor instability, the hydrodynamic instability most likely to preclude high gain in high-convergence (initial outer DT fuel radius to final compressed fuel radius ratio greater than 30), high-aspect-ratio (fusion target shell radius divided by the shell thickness greater than 40) target implosions of interest to ICF, have shown less than classical growth rates.[12]

An especially notable achievement, made possible by the ICF program, was the observation of amplified spontaneous emission of soft x-ray wavelengths (206.3 and 209.6 Å) from a laser ionized selenium foil. This was the first laboratory demonstration of a soft x-ray laser amplifier.[13] X-ray laser development is one of a number of scientific dividends which has resulted from the ICF program.

The major driver facilities, plasma diagnostics, target design capabilities, and target fabrication resources required to demonstrate the scientific feasibility of inertial fusion are now nearly in place. Experimental data on scale models of high-gain targets which will be conducted in the near future should give increased confidence that high-gain (greater than 100) performance can be achieved. On the basis of experiments to be performed in the next few years, options for ICF can be narrowed. Research on high-efficiency drivers (lasers or particle beams) should determine, together with target performance data, the optimal path to success.

Robert L. McCrory, Jr., Laboratory for Laser Energetics, University of Rochester

1. R. L. McCrory, Laser Focus **21**, 9 (1985).
2. J. P. VanDevender, J. A. Swegle, D. J. Johnson, K. W. Bieg, E. J. T. Burns, J. W. Poukey, P. A. Miller, J. N. Olsen, and G. Yonas, Laser Particle Beams **3**, 93 (1985); S. Nakai *et al.*, Proc. of The Japan–U. S. Seminar on Theory and Application of Multiply Ionized Plasmas Produced by Laser and Particle Beams, Nara, May 3, 1982, ILE, Osaka, 1982.
3. J. L. Emmett, Presentation to the National Academy of Sciences Inertial Confinement Fusion Review, 30 May, 1985.
4. R. L. McCrory, Laser Focus **21**, 10 (1985).
5. R. Jensen, Los Alamos National Laboratory (private communication).
6. R. L. Keck, L. M. Goldman, M. C. Richardson, W. Seka, and K. Tanaka, Phys. Fluids **27**, 2762 (1984).
7. R. E. Turner, K. Estabrook, R. L. Kauffman, D. R. Bach, R. P. Drake, D. W. Phillion, B. F. Lasinski, E. M. Campbell, W. L. Kruer, and E. A. Williams, Phys. Rev. Lett. **54**, 189 (1985).
8. P. D. Goldstone *et al*, Digest of Technical Papers Conference on Lasers and Electro-Optics, 21 May, 1985, Optical Society of America, Washington, 1985.
9. S. P. Obenschain *et al.*, Digest of Technical Papers, Conference on Lasers and Electro-Optics, Anaheim, 19 June, 1984, Optical Society of America, Washington, 1984.
10. F. Ze *et al.*, Lawrence Livermore National Laboratory Report, UCRL-91087, Livermore (1984).
11. R. L. McCrory and J. M. Soures, Nucl. Fusion **25** (1985).
12. J. Wark *et al.*, Annual Report to the Laser Facility Committee, 1984, Rutherford Appleton Laboratory, pp. 2–37 (1984).
13. D. L. Matthews *et al.*, Phys. Rev. Lett. **54**, 110 (1985).

Equilibrium of Totally Unneutralized Plasmas

Plasmas that contain only a single sign of charge, such as pure-electron or pure-ion plasmas, have unique and interesting confinement and equilibrium properties. In principle, these plasmas can be confined to a given region forever; in practice, confinement times of hours or even days are obtained. These relatively isolated and quiescent plasma samples are finding a number of applications in physics and technology.

The confinement of unneutralized plasmas is achieved in a simple cylindrical geometry: a uniform axial magnetic field provides the radial confinement, and dc voltages applied to end electrodes provide the axial confinement. The confined plasma has a rounded cylindrical shape, and it rotates about its axis. The rotation through the magnetic field provides an inward force, which balances the outward forces caused by the unneutralized charge and the plasma pressure.

The unique confinement properties of totally unneutralized plasmas derive from conservation of angular momentum. To the extent that there are no external torques on such a plasma, the mean square radius of the plasma is conserved; there can be no bulk expansion of the plasma. In contrast, neutral plasmas have no similar confinement constraint.

After a sufficiently long time, the particles in an isolated unneutralized plasma must come into thermal equilibrium with each other, through internal transport of particles and energy. If different parts of the plasma are initially at different temperatures, interparticle collisions cause thermal energy to diffuse from hot areas to cold areas, and the plasma

FIG. 2. The OMEGA glass laser system at the University of Rochester.

becomes isothermal. If different parts of the plasma are rotating at different rates (that is, if there is shear in the rotational flow), interparticle collisions give rise to viscous forces, and these produce particle transport to a density profile characterized by rigid rotation.[1] This transport is unusual in that it involves only a rearrangement of the plasma particles (the mean square radius of the plasma is conserved), rather than a diffusive spreading of the plasma. Similar (like-particle) collisional transport can occur because of collisions within each species of neutral plasma, but is typically masked by the much larger diffusion owing to collisions between particles belonging to different species.

This internal transport towards thermal equilibrium has been measured recently in a pure electron plasma apparatus at the University of California at San Diego. As expected, the plasma evolves to a uniform-temperature, rigid-rotor equilibrium. Also, the mean square plasma radius is conserved to good accuracy. However, the rate of particle transport differs substantially from the predictions of traditional like-particle transport theory: the rate is much larger and depends more weakly on magnetic field strength than predicted. These experiments may be thought of as measuring the viscosity of a magnetized electron plasma.

Recent development of a new theory may explain the enhanced viscosity and transport rate.[2] The new theory considers the effect of a subtle kind of collisional interactions between well-separated particles. In the new theory, the interacting particles can be separated by as much as a Debye shielding distance (the distance beyond which interactions are strongly attenuated), whereas in the traditional theory they can be separated by no more than a cyclotron radius (the size of individual particle orbits in the magnetic field). The new theory is consistent with the preliminary experimental results.

The existence of stable, quiescent equilibria is central to several other unneutralized plasma applications. At UCSD, the apparatus is designed to cool an electron plasma to the liquid or crystal states, using cyclotron radiation to decrease the total energy of the near-equilibrium states.[3] At the National Bureau of Standards in Boulder, Colorado, tuned lasers are used to cool ion plasmas to cryogenic temperatures, both to study the liquid and crystal states, and also to serve as the basis for a proposed frequency standard.[4] Similar ion clouds can be used to study atomic physics and chemical reactions.[5] At Bell Labs, an apparatus to contain a pure positron plasma is being developed.[6] Finally, it has been suggested that pulsar magnetospheres may include unneutralized plasmas in various near-equilibrium configurations.[7]

C. F. Driscoll and T. M. O'Neil,
University of California, San Diego

1. T. M. O'Neil and C. F. Driscoll, Phys. Fluids **22**, 266 (1979).
2. T. M. O'Neil, Phys. Rev. Lett. (submitted).
3. J. H. Malmberg, T. M. O'Neil, A. W. Hyatt, and C. F. Driscoll, Proceedings of the 1984 Sendai Symposium on Plasma Nonlinear Phenomena, 1984, p. 31.
4. J. J. Bollinger and D. J. Wineland, Phys. Rev. Lett. **53**, 348 (1984); J. J. Bollinger, J. D. Prestage, W. M. Itano, and D. J. Wineland, *ibid.* **54**, 1000 (1985).
5. S. E. Barlow, G. H. Dunn, and M. Schauer, Phys. Rev. Lett. **52**, 902 (1984).
6. C. M. Surko *et al.*, in *Positrons and Solids, Surfaces and Atoms*, edited by K. F. Canter (World Scientific, 1986).
7. F. C. Michel, Rev. Mod. Phys. **54**, 1 (1982).

The Concept of Magnetic Helicity in Laboratory Plasmas

The fundamental basis of plasma physics, the interaction of classical charged particles with classical electromagnetic fields, is well understood. However, because of the large number of particles interacting with each other and with the electromagnetic fields, an exact description of the rich variety of possible plasma phenomena is not generally possible. A goal of plasma physics research is therefore to establish useful basic principles that help us to understand the behavior of natural and laboratory-produced plasmas. Such a development is illustrated by the increasing attention being given to the concept of "magnetic helicity." Magnetic helicity is a measure of the topological linkage of magnetic lines of force.[1] For example, in the case of two discrete closed flux tubes ϕ_1 and ϕ_2 that link each other, the magnetic helicity K is given by $K = 2\phi_1\phi_2$. Under certain conditions the helicity is preserved even though rather complex plasma phenomena take place.

Consider the case of a perfectly conducting vessel which is suddenly and arbitrarily filled with magnetized plasma. The magnetic fields embedded in the plasma are generated by plasma currents as well as by image currents in the conducting walls. On the relatively short time scale τ_A required for the transit of a magnetosonic wave across the plasma, pressure balance is established, but the configuration of strongly coupled fields and currents continues to evolve. On the relatively long time scale τ_R of resistive diffusion, the plasma currents and associated fields must eventually decay away. However, on an intermediate time scale (roughly the geometric mean of τ_A and τ_R), in cases for which beta, the ratio of the plasma kinetic energy to the magnetic energy, is low, it is known that the configuration will "relax" so as to minimize its total magnetic energy. Such relaxation occurs, for example, by local tearing and reconnection of magnetic lines of force. Although such relaxation might be expected to result in the rapid, turbulent annihilation of the magnetic field, this is generally not observed to be the case.

The concept of magnetic helicity is the key to understanding this behavior. It has been conjectured that the total magnetic helicity of the plasma configuration is not affected by such turbulence and is, in fact, dissipated only on the much longer resistive time scale. This conjecture, with origins in astrophysical research,[2] and in plasma physics research,[3] was proposed as an explanation for the self-reversal seen in early reversed-field-pinch (RFP) experiments.[4] Its primary consequence is that, for low beta, relaxation processes lead to unique equilibria in which magnetic energy is minimized, subject to the constraint of constant total magnetic helicity.

For these equilibria, the plasma current density (J) is parallel to the magnetic field (B) and furthermore, the ratio J/B is constant throughout the volume.

It has, therefore, been the task of recent plasma experiments to determine to what extent helicity is conserved and the predicted equilibria established. In these experiments, the actual relaxation mechanisms and their time scales are also of major concern. In the ZT-40M toroidal reversed-field-pinch experiment at Los Alamos, the degree of self-reversal observed in the toroidal magnetic field agrees well with a modified model in which J/B is constant throughout the plasma except for a thin layer near the conducting wall where it decreases. In addition, recent studies[5] of the global magnetic energy and helicity balance in ZT-40M show that, within the uncertainty of the temperature and magnetic field profiles, the dissipation of helicity is indeed controlled by simple collisional (ohmic) resistivity.

The spheromak, with a spherical boundary topology, provides another confinement geometry in which helicity conservation has been tested. In experiments at many laboratories, relaxation toward the minimum-energy configuration has been clearly seen, though differences in the observed degree of constancy of J/B do result from differences in formation technique. In the CTX experiment at Los Alamos, a magnetized coaxial plasma gun is used as a helicity source for the formation and sustainment of a spheromak configuration in an adjacent enclosure. Recent studies show that, within experimental uncertainty, all of the magnetic helicity generated in this source is conserved and transferred to the spheromak, whereas roughly 75% of the magnetic energy is lost in the relaxation process.[6]

The demonstration of helicity-conserving relaxation in RFPs and spheromaks is of major significance because it indicates how the plasma currents, and hence the confining magnetic fields, in such configurations may be indefinitely sustained. All that is required is a means for replacement of the helicity that is lost on the slow, resistive time scale. Relaxation processes do the rest. The feasibility of such methods has already been demonstrated for the reversed field pinch; and spheromak sustainment has been achieved for times greater than $10\,\tau_R$.[7] The original conjecture, that total magnetic energy relaxes on time scales for which total magnetic helicity is conserved, may be difficult to derive rigorously from Newton's laws and Maxwell's equations. However, its utility in the laboratory has already become well established.

Bradford L. Wright and Kurt F. Schoenberg,
Los Alamos National Laboratory

1. H. K. Moffatt, *Magnetic Field Generation in Electrically Conducting Fluids* (Cambridge University, Cambridge); M. A. Berger and G. B. Field, J. Fluid Mech. **147**, 133 (1984).
2. L. Woltjer, Proc. Natl. Acad. Sci. U.S.A. **44**, 489 (1958).
3. D. A. Wells, J. Plasma Phys. **4**, 645 (1970).
4. J. B. Taylor, Phys. Rev. Lett. **33**, 139 (1974).
5. K. F. Schoenberg *et al.*, Phys. Fluids **27**, 1671 (1984).
6. Cris Barnes *et al.*, Phys. Fluids (submitted).
7. K. F. Schoenberg *et al.*, Phys. Fluids **27**, 548 (1984); T. R. Jarboe *et al.*, Phys. Rev. Lett. **51**, 39 (1983).

Tokamak Confinement with Neutral Beam Injection

Despite intense theoretical and experimental research spanning more than a decade, the confinement of Tokamak plasmas under conditions required for controlled thermonuclear fusion remains a largely empirical science. Fortunately, the Tokamak configuration has a strong tolerance for "anomalous" processes that result in a loss of plasma fuel or energy.

As a practical matter, however, excessive loss rates would render uneconomical any device in which the fusion reaction is self-sustaining (ignited). A convenient, albeit imprecise, criterion for acceptable energy loss rates required for ignition in a device of modest size (a minor radius of 1 m) is for the electron thermal conductivity χ_e to be less than 1 m^2/sec, corresponding to an energy confinement time τ_E of more than 1 sec. Values of χ_e in this range are typical of high density ohmic data,[1] in which plasma heating arises from a current passing through the resistive plasma medium. However, except for the case of very high magnetic field strengths (greater than 10 T), the achievement of the temperatures needed for ignition requires that ohmic heating be supplemented by auxiliary heating. The first confinement experiments with the energy balance dominated by auxiliary heating were conducted by injecting moderate energy (tens of kilovolts) neutral particle beams into the plasma. Unfortunately, degradation of confinement compared to the ohmic heating data was the invariable result, the most disturbing feature being a progressive increase of χ_e with heating power.[2]

A more extensive neutral beam heated data set was recently made available through a series of experiments on the Doublet III Tokamak at GA Technologies.[3] Extending to 8 MW of injected power, this data is characterized by a value of about 1 m^2/sec for χ and electron and ion temperatures as high as 5 keV. The so-called "Lawson" quality of confinement $(n\tau_E)$ approached 10^{19} m^{-3} sec, only one order of magnitude less than that needed for ignition. The degradation of confinement with auxiliary heating power also observed in other Tokamaks was found to saturate at high power levels. In the saturated regime τ_E was proportional to the plasma current I_p and the square root of the vertical elongation of the noncircular plasma cross section. The appearance of I_p in expressions for energy confinement as well as for stability limits (the maximum permissible plasma pressure at a given magnetic field strength has been found also to be proportional to I_p), has provided valuable guidance for the design of a device that can achieve ignition.

The Doublet III data also revealed that a number of easily implemented operating procedures can favorably influence the numerical value of τ_E. For example, τ_E increases both with plasma ion mass and with beam-injected ion mass, two dependencies that extrapolate favorably to reacting plasmas. Of broader significance is the improvement of energy confinement when the plasma edge is determined by a magnetic boundary, or divertor, instead of a material boundary, or limiter. This improvement has also been observed on other Tokamaks.

In extending confinement studies to progressively more reactor-like conditions, two issues stand out. One is the degree of sensitivity of the findings to the specific form of auxiliary heating. Comparisons between electron cyclotron heating and neutral beam injection on Doublet III and between ion cyclotron heating and neutral beam injection on the Princeton Large Torus Tokamak suggest that the level of sensitivity is not great. The second key issue is the scaling with plasma size. The similarity of development paths pursued by all the major participants in the magnetic fusion research worldwide has resulted in an auxiliary-heated confinement data base that covers a surprisingly narrow range of plasma size. The new generation of larger Tokamaks—TFTR at Princeton, JET in England, and JT-60 in Japan—are just beginning to provide the data needed to resolve this issue and to explore confinement at temperatures in excess of 10 keV.

John M. Rawls, GA Technologies Inc.

1. M. Greenwald *et al.*, Phys. Rev. Lett. **53**, 352 (1984).
2. A compilation of earlier data is found in R. Goldston, Control led Fusion and Plasma Phys. (Proc. 11 the European Conf. Aachen, 1983), Vol. 26, European Phys. Soc. 87 (1984).
3. K. H. Burrell *et al.*, *Plasma and Controlled Nuclear Fusion Research* (*Proc. 10th Int. Conf., London, 1984*) (IAEA, Vienna, 1985), Vol. I, p. 131.

POLYMER PHYSICS

High Polymer Physics is an interdisciplinary branch of materials science devoted to the structure and properties of substances composed of very long molecules. Polymers of natural origin have long been numbered among technologically useful materials, but attention has for some time been concentrated upon synthetic polymers. The range of molecular structures which can be produced and the variety of physics states (glassy, rubbery, liquid–crystalline, and crystalline) in which they may exist offer diverse opportunities for designed control of mechanical, thermal, and electrical properties. These opportunities are further enhanced by the admixture of different species in polymer blends. The following articles describe new developments in methods for characterizing chemical structure and molecular motion in polymers, in the study of liquid–crystalline polymers, and in the understanding of phase equilibria and phase separation in polymer blends.

H. D. Keith, AT&T Bell Laboratories

Nuclear Magnetic Resonance

An important new technique for detailed analysis of the microstructure of a polymer chain is the use of two-dimensional nuclear magnetic resonance (NMR).[1] This involves separation of chemical shifts, the slight departures in the NMR spectrum of an element when it is a constituent in a complex molecule from the spectrum for a sample containing that element in pure form. In the new technique, the chemical shifts are made along two orthogonal axes. This method simplifies interpretation of spectra by permitting unambiguous assignment of peaks in most cases and by greatly reducing the need for reliance upon guesswork and comparison with model compounds. Its introduction has stimulated a considerable revival of interest in proton NMR spectroscopy of synthetic polymers, a subject which declined in importance with the advent some years ago of carbon-13 NMR spectroscopy. Complete determination of structure in polymer chains can now be accomplished on the basis of but a few well-chosen 2D-NMR experiments.

Capability for precise determination of the amplitude and frequency of molecular motions in bulk polymers has been revolutionized by the use of solid-state deuterium NMR[2] and carbon-13 dipolar rotational echo spectroscopy.[3] It is now possible to correlate accurately characterized motions with dielectric and mechanical relaxations.

Another technique, as yet in its infancy, is NMR imaging of solid polymers.[4] This offers great promise for the examination of structure, morphology, and molecular motion with a spatial resolution potentially well below 1 millimeter. Useful application has already been made to the study of inhomogeneous uptake of moisture in epoxy resins; many other applications can be foreseen.

L. W. Jelinski, AT&T Bell Laboratories

1. M. D. Bruch and F. A. Bovey, Macromolecules **17**, 978 (1984).
2. L. W. Jelinski, Annu. Rev. Mater. Sci. **15**, 359 (1985).
3. J. Schaefer, E. O. Stejskal, R. A. McKay, and W. T. Dixon, Macromolecules **17**, 1479 (1984).
4. W. P. Rothwell, D. R. Holecek, and J. A. Kershaw, J. Polym. Sci., Polym. Phys. Ed. **22**, 241 (1984).

Liquid–Crystalline Polymers

It has long been recognized that because of their low densities, long chain polymers should exhibit unique strength/weight ratios, provided that the covalently bonded backbones of the molecules can be fully oriented. Achievement of ultraorientation is thus central to technological production of high-performance materials. New polymers that exhibit lyotropic (solvent-induced) or thermotropic (thermally induced) liquid–crystalline states are exciting considerable current interest because of inherent alignment of chains within fluid phases.[1] Kevlar, a well-known high-modulus, high-strength, high-temperature fiber produced by E. I. DuPont de Nemours, is prepared by spinning from a lyotropic liquid–crystalline solution. A key feature is the easy alignment of rod-like molecules in the flowing solution and its subsequent preservation as solvent is removed.

The presence of solvent, however, imposes restrictions on processing, and efforts are being directed to the use of thermotropic liquid–crystalline polymers for many applications. These are mostly aromatic polyesters having fairly stiff chains whose alignment during processing can similarly be preserved during subsequent cooling into glassy or semicrystalline states. Transition temperatures can be controlled by co-polymerization using different aromatic monomers. Research centers upon understanding the influence of molecular structure on ordering in liquid–crystalline phases and upon phase transition phenomena.

E. L. Thomas, University of Massachusetts

1. Roy. Soc. Chem. Faraday Discussion No. 79, 1985.

Isotope Effects in Polymer Melts

Relatively large differences in mass and in the neutron scattering cross section between hydrogen and deuterium nuclei have been widely exploited for some time in studies of chain conformation and phase equilibria in polymers and polymer blends. Implicit in this work have been the assumptions that hydrogenated and deuterated species of otherwise identical chemical structure form ideal solutions and that substitution of one for the other is without significant effect upon phase equilibria in amorphous polymer blends. Recent studies have shown, however, that critical temperatures for phase separation in blends of different polymers are significantly altered by isotopic labeling of one component.[1,2]

In the case of blends of polystyrene and poly(vinylmethylether), the lower critical solution temperature is elevated dramatically by substitution of perdeuteropolystyrene for its hydrogenated equivalent.[2] Current work at AT&T Bell Laboratories and at the National Center for Small-Angle Scattering Research (Oak Ridge National Laboratory) on blends of normal and perdeuterated polybutadienes, polymers which differ only in that one is labeled and the other is not, has now revealed that even in these cases mixing is not ideal.[3] Small angle neutron scattering data obtained for these blends demonstrate conclusively the existence of upper critical solution temperatures. This isotope effect is clearly attributable to the fact that segments of hydrogenated and deuterated molecules occupy slightly (less than 1%) different volumes.[4] For polybutadiene chains containing more than 2300 monomers, the small entropy gained by mixing such large molecules is counterbalanced by a loss in entropy associated with the difference in monomeric volume, and phase separation results.

These findings have important consequences for polymer physics research in general. Even in what are nominally homopolymers, deuterium labeling must be employed with caution in studying properties that may be influenced by nonideal mixing of host and labeled species. On the other hand, controlled use of isotope effects can be employed to advantage in developing better understanding of phase separation phenomena in polymer melts.

F. S. Bates, AT&T Bell Laboratories

1. E. L. Atkin, L. A. Kleintjens, R. Konigsveld, and L. J. Fetters, Makromol. Chem. **185**, 377 (1984).
2. H. Yang, G. Hadziioannou, and R. S. Stein, J. Polym. Sci., Polym. Phys. Ed. **21**, 159 (1983).
3. F. S. Bates, G. D. Wignall, and W. C. Koehler, Phys. Rev. Lett. (submitted).
4. A. D. Buckingham and H. G. E. Hentschel, J. Polym. Sci., Polym. Phys. Ed. **18**, 853 (1980).

Dynamics of Phase Separation in Polymer Blends

Recent studies of binary polymer blends have highlighted areas of similarity and dissimilarity between phase separation in these systems and corresponding behavior in metallic alloys, inorganic glasses, and systems consisting of small molecules. If time and length are properly scaled, data on the dynamics of phase separation in polymer blends are roughly superimposable upon similar data for these simpler systems.[1]

Relative to molecular dimensions, concentration fluctuations in polymers occur on a small scale, even near a critical point, and critical behavior should therefore be amenable to analysis using mean-field approximations.[2] The validity of this approach has recently been substantiated by neutron scattering measurements of correlation lengths and osmotic compressibilities carried out in Europe[3] and in the United States.[4] The classical theory of spinodal decomposition (a transition that is unstable to fluctuations) should also be applicable to polymer blends and this has now been demonstrated convincingly during early stages of phase separation in blends of polystyrene and poly(vinylmethylether).[5]

At later stages, however, separation proceeds by a different mechanism. The bicontinuous network initially produced becomes unstable under the action of pressure gradients generated at diffuse phase boundaries. The network breaks up and separate domains then begin to grow linearly in time. Such a mechanism had been anticipated theoretically[6] and is now established experimentally.

C. C. Han and I. C. Sanchez, National Bureau of Standards

1. H. L. Snyder and P. Meakin, J. Chem. Phys. **79**, 5588 (1983).
2. P. G. DeGennes, J. Phys. (Paris) Lett. **38**, L441 (1977); J. F. Joanny, J. Phys. A **11**, L117 (1978).
3. C. Herkt-Maetzky and J. Schelten, Phys. Rev. Lett. **51**, 896 (1983).
4. H. Yang, M. Schibayama, R. S. Stein, and C. C. Han, Polym. Bull. **12**, 7 (1984).
5. C. C. Han, *et. al.*, Proceedings of the SPE 43rd Annual Technical Conference and Exhibition, 1985, p. 305.
6. E. D. Siggia, Phys. Rev. A **20**, 595 (1979).

VACUUM PHYSICS

Vacuum physics includes those areas of research and technology for which the production, maintenance, and measurement of a vacuum and its materials processing are significant. This includes studies of chemical reactions on solid surfaces, the production and properties of thin solid films, vacuum metallurgy, vacuum surface phenomena occuring in plasma fusion research, deposition and vacuum processing of electronic materials, and studies of the geometric and electronic structure of surfaces and solid–solid interfaces.

A New Family of Epitaxial Dielectrics

Dielectric films on silicon substrates form the basis of insulated-gate field effect transistors, which are used in a wide range of large-scale integrated circuits in the semiconductor industry. The dielectrics most commonly used at present are the amorphous oxides and nitrides of silicon. Scientists at the Westinghouse R & D Center have recently discovered a new family of dielectrics that have desirable physical and electrical properties for application in optoelectronic and microelectronic devices.[1] Some of the possible uses are in semiconductor surface passivation, as gate dielectrics in insulated gate field effect transistors, and as epitaxial interlayers for silicon-on-insulator structures.

One new family of dielectrics is the rare-earth trifluorides, which include LaF_3, CeF_3, and NdF_3. Under the proper conditions, these fluorides grow epitaxially as single crystals in a direction parallel to the so-called [111] direction of the silicon substrate crystal. This direction is defined as being perpendicular to the plane (or facet) of a cubic crystal which has a threefold symmetry. The electrical properties at the interface of single-crystal dielectrics are potentially better than those of their amorphous counterparts.

The growth and characterization of epitaxial dielectrics on semiconductors is a new and growing field of thin film physics which was initiated in 1981 with the successful epitaxial growth of the alkaline–earth fluoride BaF_2 on zincblende semiconductors such as InP and CdTe.[2] Shortly afterwards, epitaxial growth of CaF_2 on silicon was reported.[3,4] Since 1981 this field has grown rapidly and has led to exciting discoveries in both pure and applied areas.

For example, a new and unexpected type of interface between a single-crystal substrate and epitaxial film has been discovered,[5] the incommensurate interface, and much has been learned of the controlling role of overlayer surface free energy[6] in determining the growth and structural perfection of the epitaxial fluorides.

Prototype field effect transistor devices based on epitaxial CaF_2 on Si substrates (in the [100], or fourfold symmetry orientation) have already been fabricated and exhibit highly promising performance.[7,8] Nevertheless, there is a need for epitaxial dielectrics that are water insoluble, mechanically hard, and that have good structural and electrical properties on the [111] surfaces of semiconductors. We have shown that the family of rare-earth fluorides LaF_3, CeF_3, and NdF_3 possess these desirable properties. These hexagonal-structure materials have been deposited on atomically clean Si [111] surfaces in ultrahigh vacuum. Dielectric breakdown strengths of greater than 5×10^6 V/cm have been measured.

In addition to applications of the rare-earth[4] fluorides in semiconductor devices, we believe that opportunities now exist for engineering thin film device structures with a variety of useful optical and electrical properties. For example, it should be possible to introduce piezo and ferroelectricity into fluoride films by co-evaporation of BaF_2 and MgF_2 to form $BaMgF_4$. In summary, this new discovery opens up a wealth of opportunities in materials engineering and thin film physics.

R. F. C. Farrow, S. Sinharoy, R. A. Hoffman, and T. A. Temonfonte, Westinghouse R & D Center, Pittsburgh, PA

1. S. Sinharoy, R. A. Hoffman, J. H. Rieger, W. J. Takei, and R. F. C. Farrow, J. Vac. Sci. Technol. B **3**, 722 (1985).
2. R. F. C. Farrow, P. W. Sullivan, G. M. Williams, G. R. Jones, and D. C. Cameron, J. Vac. Sci. Technol. **19**, 415 (1981).
3. H. Ishiwara and T. Asano, Appl. Phys. Lett. **40**, 66 (1982).
4. P. W. Sullivan, T. I. Cox, R. F. C. Farrow, D. Gasson, and C. S. Smith, J. Vac. Sci. Technol. **20**, 731 (1982).
5. J. M. Gibson and J. M. Phillips, Appl. Phys. Lett. **43**, 828 (1983).
6. L. J. Schowalter, R. W. Fathauer, R. P. Goehner, L. G. Turner, R. W. DeBlois, S. Hashimoto, J. L. Peng, W. M. Gibson, and J. P. Krusius, J. Appl. Phys. **58**, 302 (1985).
7. T. P. Smith III, J. M. Phillips, w. M. Augustyniak, and P. J. Stiles, Appl. Phys. Lett. **45**, 907 (1984).
8. T. Asano, Y. Kuriyama, and H. Ishiwara, Electron. Lett. **21**, 386 (1985).

Long-Range Order in III–V Semiconductor Alloys

Contrary to expectations, Ga and Al atoms have been shown to form an ordered sublattice in $Al_xGa_{1-x}As$ epitaxial layers grown on GaAs.[1] Such long-range order has never before been observed in any III–V type semiconductor alloy. Important questions are thus raised concerning the equilibrium phase of that system and the stability of certain types of artificially grown superlattice structures.

Among all semiconductor alloys, the $Al_xGa_{1-x}As$ system has been most intensively studied, primarily because of its wide application in optoelectronics and in high-speed devices. The importance of this alloy system is based on its close lattice match to GaAs and on its energy gap, which varies strongly with alloy composition. These are properties that make the material ideal for use in heterojunction devices.

$Al_xGa_{1-x}As$ is a solid solution, with Ga and Al atoms sharing the same sublattice. Until the work described here, the occupancy of Ga and Al atoms in this sublattice had always been thought to be completely random. Moreover, it was believed that this configuration represented a state of thermodynamic equilibrium.

The long-range order was found in thin layers of $Al_xGa_{1-x}As$ (with x lying between 0.25 and 0.75) grown epitaxially on GaAs substrates at temperatures between 650 and 800 °C using metal-organic vapor-phase epitaxy (MOVPE) or molecular beam epitaxy (MBE) techniques. The ordering was detected through the transmission electron diffraction patterns from these layers; the patterns show extra reflections that should be forbidden in a disordered or random state, and which clearly indicate that certain sites in each unit cell are preferred by Ga atoms and others by Al atoms. A perfectly ordered state in $Al_{0.5}Ga_{0.5}As$, for example, consists of alternating AlAs and GaAs monolayers, and, once ordered, remains stable at temperatures below the growth temperature.

This ordered state is equivalent to a monolayer superlattice structure that was fabricated artificially in the past by alternate depositions of monolayers of GaAs and AlAs on a GaAs surface at about 600 °C by MBE.[2] This would require repeated manipulation of shutters that control the flux of Ga and Al atoms. During the high-temperature growth, AlAs and GaAs layers are expected to be fully miscible and it was considered surprising that a monolayer superlattice could be synthesized at all.

Now it is even more surprising that this monolayer segregation can occur during a continuous co-deposition of Al, Ga, and As at high temperature without any artificial imposition of special growth sequences. Thus, the IBM investigators believe it is likely that the segregated and ordered structure represents the equilibrium and thermodynamically stable state. What prevented the ordered state from being found before is that the state is difficult to reach in bulk $Al_xGa_{1-x}As$ through the very slow bulk diffusion process. It is possible that ordered stable phases may also exist in other III–V alloy systems in which monolayer superlattice structures have been fabricated.[3,4] Recent theoretical calculations suggest that an ordered phase can also be stable in $Ga_xIn_{1-x}P$ systems.[5]

The atomic processes in a MOVPE and MBE growth are not very well understood. Thus, the atomic processes responsible for the growth of the ordered structure are unclear. The formation of ordered structures seems to rely on very fast surface diffusion of Ga and Al atoms. Above 800 °C the long-range order ceases to exist and at temperatures below 600 °C the ordered state cannot be reached either, presumably because of insufficient surface mobilities of Al and Ga atoms during the growth. The degree of order achievable is higher in MOVPE-grown layers and less pronounced in MBE-grown material; no sign of ordering has yet been detected in liquid phase epitaxy (LPE) grown material. The observation of the onset of ordered structure under different growth conditions may give us clues as to their difference in growth mechanism.

The ordered III–V semiconductor phases are expected to have interesting optical and electrical properties that are different from those in the corresponding disordered phases. The search for new ordered III–V phases and the exploration of their properties is certain to draw the attention of many researchers in the near future.

T.S. Kuan, IBM T.J. Watson Research Center

1. T. S. Kuan, T. F. Kuech, W. I. Wang, and E. L. Wilkie, Phys. Rev. Lett. **54**, 201 (1985).
2. A. C. Gossard, P. M. Petroff, W. Wiegmann, R. Dingle, and A. Savage, Appl. Phys. Lett. **29**, 323 (1976).
3. Y. Hirayama, Y. Ohmori, and H. Okamoto, Jpn. J. Appl. Phys. **23**, L488 (1984).
4. T. Fukui and H. Saito, Jpn. J. Appl. Phys. **23**, L521 (1984).
5. G. P. Srivastava, J. L. Martins, and A. Zunger, Phys. Rev. B **31**, 2561 (1985).

PHYSICS NOBEL PRIZE

Klaus von Klitzing of the Max Planck Institute for Solid State Research in Stuttgart, West Germany won the 1985 Nobel Prize in physics for his discovery of the quantum Hall effect.

Named for the 19th century physicist Edwin Hall, the Hall effect, known for many years, is a phenomenon in which an electric field and a perpendicular magnetic field, applied to a conductor, induces an electric current at right angles to both fields. The ratio of the current to the size of the electric field is called the Hall conductance.

As applied to semiconductors, the Hall effect can take an interesting form. In some circumstances a thin layer of mobile electrons, called an inversion layer, exists at the surface of a semiconductor. The layer can carry current in the plane of the surface, and when a magnetic field, supplied by an external magnet, is applied perpendicular to the surface, a Hall conductance can be observed. The number of mobile electrons in the layer changes when an electric field is also applied perpendicular to the surface and this changes the Hall conductance of the layer.

At low temperatures and high magnetic fields the Hall conductance is quantized in integral multiples of e^2/h, where e is the charge of the electron and h is Planck's constant. In other words, the Hall conductance changes in abrupt steps (the quantized Hall effect) as the number of electrons in the inversion layer is changed. von Klitzing and his colleagues first observed this effect in a silicon metal-oxide-semiconductor field effect transistor (MOSFET) at a temperature of 1.5 K and using a magnetic field of 15 T.[1]

The initial experimental measurements were in agreement with theory (quantum electrodynamics) to within a few parts per million,[2] raising the possibility that the fine structure constant could be independently measured with an unprecedented precision. This in turn would facilitate important tests of quantum electrodynamics itself.

Later experiments have shown that the Hall conductance can be fractionally quantized, a phenomenon which has not yet been satisfactorily explained.[3]

Phillip F. Schewe

1. K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
2. *Physics News in 1981*, p. 33; *Physics News in 1982*, p. 41; Phys. Today **34**, 17 (June 1981).
3. *Physics News in 1983*, p. 34; Phys. Today **36**, 19 (July 1983).