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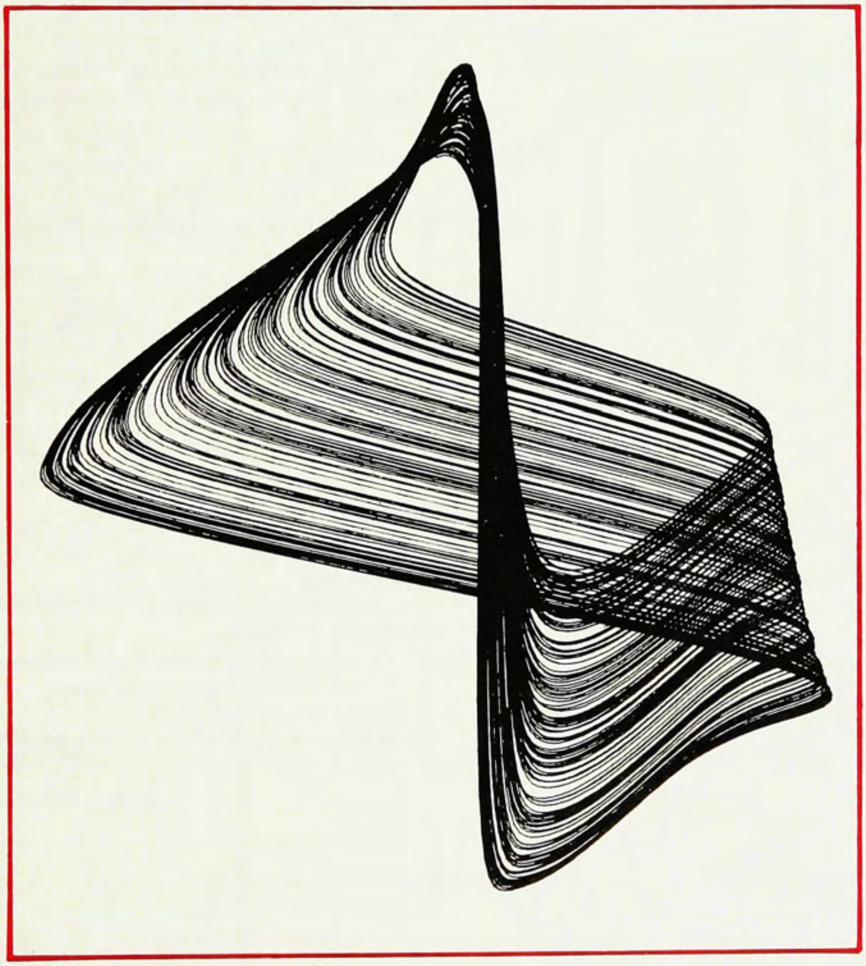
PHYSICS NEWS IN 1983



Phillip F. Schewe, Editor

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COVER: A phase-space portrait of an oscillating chemical reaction. (Figure supplied by Harry Swinney of the University of Texas.) See page 45.

PREFACE

Physics News in 1983 is the 15th in a series of annual reports designed to call attention to some of the interesting and newsworthy developments in physics and related fields during the past year. Prepared by the Public Information Division of the American Institute of Physics, *Physics News* has usually been published only in book form and distributed to science journalists, students, Congress, and the general public. This year it appears in *Physics Today* in order to make it available to the entire physics community as well. The articles for *Physics News 1983* were chosen and prepared by representatives of the AIP Member Societies. I should like to thank, in addition to those who wrote articles, the following people for helping to organize the material appearing in *Physics News:*

The American Physical Society

Plasma Physics Division—Francis Chen, UCLA; Nuclear Physics Division—George Bertsch, Michigan State University; Astrophysics Division—Carl Fichtel, Goddard Space Flight Center; Electron and Atomic Physics Division—Eugen Merzbacher, University of North Carolina; Condensed Matter Division—Miles Klein, University of Illinois; Fluid Dynamics—Charles Treanor, Calspan Corporation.

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1 November 1983 Phillip F. Schewe

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ACOUSTICS

Acoustics is the study of the production, transmission, and effects of sound. Subsidiary areas of research include bioacoustics, the study of music and musical instruments, speech communication, psychological acoustics, physiological acoustics, acoustic signal processing, the effect and control of noise, mechanical vibrations and shock, ultrasonics, underwater sound, aeroacoustics and atmospheric sound, nonlinear acoustics, and acoustic holography.

Acoustic Microscopy in Superfluid Helium

The acoustic microscope is an instrument which uses focused sound waves to image a sample.[1] Plane waves in a solid are generated by a piezoelectric transducer and are brought to a focus in a liquid by refraction across a curved surface. The sample is placed near the focus. To form an image, the intensity of the echo is recorded as the lens is mechanically scanned across the sample.

Higher resolution for the microscope is obtained using shorter wavelengths (as with the optical microscope). There is a limitation on short wavelengths imposed by sound attenuation in normal fluids. However, there is one fluid in which there is little attenuation for sound waves—superfluid helium at very low temperatures below 0.1 °K. At these temperatures, helium displays the characteristic superfluid qualities. These include fluid flow without friction and the almost infinite conduction of heat at the speed of sound.

Superfluid helium is the ultimate fluid for acoustic microscopy and has been used successfully to form very-high-resolution images. With an acoustic wavelength of 550 Å, about 1/10 the wavelength of visible light, sub-500-Å resolution images have been recorded.[2] The source of contrast is generally the topographical features of the sample, although subsurface imaging techniques are currently being tried.

Many technologies have been employed in the development of the superfluid helium acoustic microscope. Low-temperature physics and cryogenic techniques, microwave and radar engineering, and nonlinear acoustic theory have all contributed to the operation and understanding of the instrument. For example, the necessary technology for low-noise preamplification of the microwave signal (4-GHz frequency) was provided by radio astronomers. With the help of these advancing fields, acoustic microscopy with 50-Å resolution is now an active subject for future research in this field.

John Foster and C. F. Quate, Stanford University

1. Calvin Quate, Sci. Am. **241**, 62 (October 1979).
2. J. S. Foster and D. Rugar, Appl. Phys. Lett. **42**, 869 (May 1983).

Microelectrode Arrays for the Profoundly Deaf

Scientists at Stanford University are trying to develop an artificial "inner ear" for the profoundly deaf which would work by direct injection of electrical signals into the auditory nerve.[1]

The ear is a transducer which converts the mechanical energy of a sound pressure wave into a set of electrical impulses which travel up the auditory nerve. The special neurons which do the transduction are the hair cells, roughly 15,000 in number, which are lined up along the basilar membrane in the cochlea, or inner ear. When the basilar membrane is flexed by the passing sound wave, the hair cells generate an electrical signal. This signal is picked up, converted to a digital signal by the "spiral ganglion" cells, and the resulting electrical pulse transmitted along the auditory nerve, which is comprised of the axons of the 30,000 ganglion cells.

If the hair cells are defective or missing (as the result of trauma, drug reaction, or genetic defect) profound deafness results, and conventional hearing aids are of no value. It is, in principle, possible to bypass the defective cochlea and insert electrical signals directly into the auditory nerve, tricking the brain into thinking that the ear is working. It has been known, in fact, for nearly two centuries since the time of Volta and Galvani, that electrical stimulation of the auditory nerve results in the perception of sound. Only in recent decades, however, has it been technically feasible to inject into the auditory nerve a signal of sufficient complexity to capture the essential features of speech.

The objective of the artifical ear project at Stanford is to develop a prosthesis of sufficient sophistication which would allow unaided speech comprehension. Such a prosthesis requires several components: (1) a microelectrode array capable of separately stimulating several discrete and distinct sets of auditory nerve fibers; (2) an implantable stimulation electronics unit for driving the electrode array; and (3) an external speech processor which receives the incoming sound, encodes it properly, and transmits data and power to the implanted unit. An electrode array, using thin-film technology, has been tested with satisfactory results.[1]

The auditory nerve may be stimulated in the required discrete manner either by a long flexible electrode array which is slid into a chamber of the coiled cochlea or by a shorter rigid array which impales the auditory nerve as it exits the cochlea. Marginally acceptable electrodes for such proposes have been fabricated using fine wire bundles and silastic molds to hold them together. The dimensions and precisions required are, however, on the very outside edge of what is achievable using bent wire technology. On the other hand, the required dimensional precision, on the order of tens of microns, is trivially achievable using the photolithographic technology common to the semiconductor industry. The Stanford scientists have been developing both flexible and rigid thin film electrodes for the cochlear prosthesis.

Neutrostimulation electrodes must be fabricated with materials that are biocompatible and which will survive decades of immersion in an actively hostile saline environment. Materials such as platinum or Teflon are biocompatible because they are chemically inert. The corollary of this inertness is that they do not adhere well to anything, much less one another. The compelling problems in the fabrication of thin-film cochlear elctrodes, then, have been those of achieving adhesion between successive layers of the laminar structure, achieving insulation layers which, though only microns thick, will last for decades, and minimizing electrolysis effects on the metals involved. After several evolutionary generations, the rigid and flexible electrode designs may now be satisfactory. The rigid electrodes use a single-crystal sapphire substrate, tantalum conductor metal with tantalum oxide and silicon nitride insulation, and platinum or iridium stimulation site metal. The flexible electrodes are a polyimide–platinum–polyimide or a polyimide–iridium–polyimide sandwich, with appropriate holes etched for lead attachment and for stimulation. These electrodes are now being tested to determine their appropriateness for human use.

A group in Melbourne, Australia has tested a device which consists of a small receiver–stimulator (20×6 mm in size) implanted in the mastoid bone behind the ear, an external microphone worn above the ear, and a speech processor ($13 \times 8 \times 2$ cm in size) carried in the pocket.[2] Recent clinical results have shown that the device has improved the patients' comprehension of running speech, particularly when used in conjuction with lip reading.

Robert L. White, Stanford University

1. R. L. White, L. A. Roberts, and O-H. Kwon, J. Acoust. Soc. Am. Suppl. **72**, S61 (1982).
2. G. M. Clark *et al.*, J. Acoust. Soc. Am. (in press); R. C. Black, A. C. Steel, and G. M. Clark, Acta Oto-Laryngol. **95**, 27 (1982).

Sound Absorption in Seawater

The use of underwater sound[1] in ocean technology is widespread, primarily because the sea is salty. Since penetration by radio waves into seawater is severely limited by ionic conduction, sound remains the most effective means for the transmission of information in this environment.

Some of the salts that contribute to electrical conductivity also affect sound propagation by increasing absorption—the gradual loss of sound energy by conversion into heat. Because absorption limits effective range, a detailed knowledge of the absorption processes is required for prediction purposes.

In freshwater, viscous effects produce absorption that increases as the square of the frequency of the acoustic signal. Therefore, if losses at a given range in fresh water should become intolerably large, one might simply reduce the frequency to achieve an acceptable condition.

In seawater, however, the situation is more complex because chemical equilibria can alter the compressibility of the medium. If the reaction rate is comparable to the acoustic frequency, relaxational absorption may also occur. The result is that when the acoustic frequency is reduced below the relaxation frequency, the absorption becomes greater than before.

By the end of the Second World War, it had been discovered that sound absorption in the sea is some 25 times greater than that in freshwater. Laboratory measurements of synthetic seawater by a resonator method showed magnesium sulfate to be responsible for the excess.[2] The pertinent chemical equilibrium was identified as a multistep dissociation process. The relaxation frequency in question—nominally 100 kHz—is above the normal acoustic range and, therefore, had previously escaped detection.

In the 1950s, military interests shifted to longer ranges and lower frequencies. Propagation measurements subsequently showed an apparent relaxation near 1 kHz with absorption values some ten times greater than that predicted by the magnesium sulfate relaxation.[3]

Laboratory investigation of the relaxation mechanism in the low-frequency range by observing temperature jumps showed that the chemical responsible for absorption was boric acid—a very minor constituent of seawater.[4] The mechanism evidently involved ionization of boric acid to form the borate ion. However, there are two possible mechanisms in seawater. One is by direct association with the hydroxyl ion and the other by exchange with the carbonate ion which is in much greater concentration. Temperature-jump measurements appeared to support two-step association.

Recent investigations of synthetic seawater by the resonator method[5] now indicate that both reactions occur. The exchange reaction, however, dominates primarily because of calcium carbonate formation which enhances absorption by a factor of 10. Without this enhancement, the seawater absorption would be negligible.

The laboratory measurements also confirm the earlier ocean measurements which showed that the excess absorption depends strongly on local acidity. Lower values of *p*H found in the North Pacific Ocean (with a *p*H of about 7.7) result in boric-acid absorption lower by a factor of 2 compared to other "normal" ocean regions (with a *p*H of about 8).

R. H. Mellen, B & K Dynamics, Inc., New London, Connecticut

1. R. J. Urick, *Principles of Underwater Sound for Engineers* (McGraw–Hill, New York, 1967).
2. O. B. Wilson and R. W. Leonard, J. Acoust. Soc. Am. **26**, 223 (1954).
3. W. H. Thorp, J. Acoust. Soc. Am. **38**, 648 (1965).
4. E. Yeager, F. H. Fisher, J. Miceli, and R. Bressel, J. Acoust. Soc. Am. **53**, 1705 (1973).
5. R. H. Mellen, D. G. Browning, and V. P. Simmons, J. Acoust. Soc. Am. **68**, 248 (1980); **69**, 1660 (1980); **70**, 143 (1981); **74**, 987 (1983).

Intrinsically Irreversible Acoustic Heat Engine

Fill a tube, having one closed end, with some gas; close it with a piston and make the piston vibrate. What happens is exactly what you would expect—the walls of the tube heat up. But when you put a stack of thermally insulating plates, spaced apart by, say, a millimeter, near the closed end of the tube and cause the piston to vibrate at acoustic frequencies, what happens is surprising. The end of the stack nearest the piston (where the gas motion and viscous heating happen to be greatest) starts to cool, while the opposite end of the stack starts to heat, and if the stack is thermally isolated, the temperature difference across the stack between piston-end and closed-end can in a few minutes get quite large, perhaps 100°C. Producing a thermal effect such as this while having to move only one part is both remarkable and potentially useful.

The significance of the work from a scientific standpoint, however, is that the above acoustic device provides, in one case, the general principles of a new class of cyclic heat engines which can use any suitable thermally active materials in which the thermal cycle is determined naturally through qualities like geometrical configuration and imperfect thermal contact. In the field of heat, especially of heat engines, it is presumptuous to imagine finding something new. Perhaps it is best to say that the acoustic experiments have led to recognition of a principle of quite general validity.

Scientists at the Los Alamos National Laboratory have recently made progress toward a working model[1] of an "intrinsically irreversible acoustic heat engine." Although the words "heat engine" usually evoke images of the steam engine, in the present context they describe an apparatus in which the concepts of heat, work, energy, and temperature are important. Some heat engines are used to turn heat into work, as in the classical steam engine; others are used to move heat from cold to hot by expending work, as in the refrigerator or the heat pump. The Los Alamos experiments thus far employed the acoustic heat pumping mode, although the same apparatus can be used, in principle, in a heat-to-cool mode by applying a large enough temperature difference.

For the words "intrinsically irreversible" we could substitute the word "natural." "Reversible" and "irreversible" are words from thermodynamics that are used to describe whether or not a given process, such as motion or heat transfer, can be reversed by an infinitesimal change in the drive. The ideal engine of Sadi Carnot (1824) is reversible and is the most efficient heat engine possible operating between two temperatures. But no real engine operating with a finite cycle time can be truly reversible. So all real engines are irreversible. What distinguishes the Los Alamos engine is that it must operate with a finite period; it ceases to function altogether as the processes become reversible. That is why it is called intrinsically irreversible.

In the acoustic engine, the irreversible process of thermal conduction, or thermal lag, introduces the concept of phase, or of "timing," into the engine. Timing in a gasoline engine means producing a spark when the piston is near top dead center. Thermal lag performs the same conceptual function in the acoustic engine except that only the piston's position is externally controlled.

In the acoustic engine, exchange of heat between the gas and the stack of plates (or really, of any other suitably porous medium) is indispensable to the engine's operation. This is a quality shared with Robert Stirling's (1816) intrinsically reversible engine. Finally, what is essential to the primary cooling and heating is the rapid change of thermal contact between gas and plates as the gas oscillates in and out of the ends of the plates; we say that this is an example of "broken thermodynamic symmetry."

So, if you cause the reciprocating mutual motion of two thermally active mediums in imperfect contact to produce thermal changes, and if you take care to break the thermodynamic symmetry, you will produce an interesting and possibly useful thermal effect in your intrinsically irreversible heat engine.

John Wheatley, Los Alamos Scientific Laboratory

1. John Wheatley, T. Hofler, G. W. Swift, and A. Migliori, Phys. Rev. Lett. **50**, 499 (1983).

The Physics of Judging a Fly Ball

Imagine the process of judging a fly ball. As soon as the ball is launched—either batted or thrown—the fielder must examine the early stages of its trajectory, decide where the ball is going to come down, and then run to the predicted landing point at an appropriate speed. The best outfielders are able to make this judgement so surely that they can turn their backs to the ball, run to the chosen spot, and wait for the ball to arrive.

One of the unique aspects of this skill is that there is no way to explain it in words, or to teach someone how to do it. There do not seem to be any coaching techniques or helpful hints that could aid the process of learning or improving one's ability to judge fly balls accurately.

If there is no conscious technique for judging a fly ball, then how is it done at all? In particular, what information does the fielder use subconsciously to decide where the ball is going to land? This subject was addressed at a recent Joint Meeting of The American Physical Society and the American Association of Physics Teachers.[1]

In 1968 Seville Chapman, a physicist at the Cornell Aeronautics Laboratory, proposed that a fielder unknowingly uses trigonometry to judge a fly ball. The specific factor identified by Chapman was the angle of elevation of the ball, the angle that a fielder's line of sight to the ball makes with the ground. Chapman claimed that the fielder sees the tangent of the angle of elevation increase at a constant rate when he is waiting at the landing point. If the ball is going over the fielder's head, he will see the tangent increase at an *increasing* rate. If the ball is going to fall in front of him, he will see the tangent increase at a *decreasing* rate. Moreover, when a fielder runs forward or backward to catch a fly ball, he does so at a speed that keeps the tangent of the angle of elevation increasing at a constant rate.

Chapman's theory of "trigonometric outfielding" was based on the assumption that air resistance does not affect the flight of a baseball in any significant way. Unfortunately, this assumption turns out to be incorrect. The effects of aerodynamic drag on the trajectory of a baseball were computed, and it was discovered that for the typical speeds and times of flight that occur under game conditions, a batted baseball travels about 60% as far as it would in a vacuum. Moreover, air resistance distorts the shape of the trajectory of the ball so that it is noticeably different from a parabola. When aerodynamic forces are accounted for, the tangent of the angle of elevation does *not* increase at a constant rate as seen by a fielder who has judged the flight of the ball correctly.

Having shown that the tangent of the angle of elevation is not a useful cue for judging a fly ball, several other geometrical or trigonometric features of the trajectory were examined, including the player–ball distance and the velocity of the ball at right angles to the line of sight (the speed with which the ball appears to move against the background of the sky).[2] None of these seems to show any characteristic variations that would tell an outfielder which direction he has to move to catch the ball. It would appear that the information used subconsciously in judging a fly ball lies at a deeper level than mere geometric or trigonometric factors.

The mystery of how a fielder judges a fly ball turns out to be one manifestation of a much larger problem. At the present time, psychologists and physiologists have only a partial understanding of how an individual determines the location in space of a rapidly moving object, or how he coordinates this information with the movement of his body. Binocular vision aids in depth perception by providing two slightly different views of the object, one from each eye, as it moves against the background. However, depth perception with a single eye is also possible; a one-eyed outfielder can, with practice, learn to judge fly balls.

It may well be that the most useful information for the fielder is not even visual information. Whenever an individual follows a moving object with his eyes, he ordinarily moves his head as well, and the motion of the head and eyes must be finely coordinated to keep the eyes fixed on the object. For example, if you fix your gaze on some stationary object and turn your head from side to side, your eyeballs must move just as rapidly in the opposite direction to maintain their lines of sight. It turns out that these compensatory motions of the eyes are primarily guided *not* by visual feedback, but rather by signals triggered by the motion of the head from sensors in the inner ear, the same sensors that enable us to tell up from down and to maintain our sense of balance.

Thus it is possible that the sudden and rapid motion of the fielder's head as he looks upward to follow the flight of the ball off the bat may provide the sensory information that directs the player's body toward the eventual landing point. This coordination of sensory input with body motion evidently follows a neural pathway that has been established through the familiar behavioral process of learning by trial and error. We may actually be judging fly balls by ear.

Peter Brancazio, Brooklyn College

1. Peter Brancazio, Paper AH-10, presented at the Joint APS-AAPT Meeting, New York, January 1983.
2. Sci. Am. **248**, 76 (April 1983).

ASTROPHYSICS

The primary concern of astrophysics has traditionally been phenomena that take place over very long periods of time. The formation of galaxies and the life of a star, for example, are measured in billions of years. Because of this and because the observation of distant astronomical objects is notoriously difficult, most studies of the sky focused on the static, rather than the dynamic, aspects of stellar and galactic evolution.

With the discovery in the past two decades of pulsars, quasars, the microwave background, and with the increasing exploitation of radiation at ultraviolet, x-ray, and gamma-ray wavelengths, scientists are addressing shorter-term, and explosive phenomena in astrophysics. Meanwhile observations at lower-energy infrared wavelengths may have uncovered evidence of a solar system other than our own.

In the past year a number of notable results have pertained to just such fleeting phenomena. These include the discovery of the fastest pulsar, the location of only the second candidate black hole, neutrons and gamma rays from solar flares, gamma-ray bursts found to coincide with the locations of transient optical bursts recorded decades before on film, and the falloff in the density of quasars at the highest red shifts.

Several articles below report on the latest results from observational programs extending over several years. These results include such topics as the large-scale structure of the universe (galaxy voids and galaxy filaments), the mysterious eclipse of the star known as epsilon Aurigae; BL Lacertae objects, which are among the most luminous in the universe; and the discovery that there is no quadrupole microwave anisotropy after all.

Finally, we report on a number of astronomical programs that are just getting off the ground, or will be in coming years. These include the new Infrared Astronomical Telescope (IRAS), the Search for Extraterrestrial Intelligence (SETI), the Space Telescope, and the future of planetary exploration at NASA.

Discovery of a Second Black Hole

The existence of black holes has been predicted for decades, but until recently only one generally accepted example was known to exist, that located in the Cygnus X-1 x-ray binary system. New observations made using the 4-m telescope at Cerro Tololo Inter-american Observatory in Chile in November 1982 show a second black hole in our nearest neighbor galaxy, the Large Magellanic Cloud.[1]

Black hole is the name given to a star which has collapsed to such a small size and enormous density that nothing can escape from it, not even light. Since black holes can emit no radiation, we can only detect their presence by the gravitational pull they exert on objects near to them. A good place to look for black holes is in binary star systems. The motion of the normal star, inferred from its light emission, may be observably affected by its nearness to a black hole.

The newly discovered black hole, called LMC X-3, is one of the two objects in such a binary system. Its companion is a faint, rather hot star about six times larger than the sun. Optical observations show that the the two objects orbit each other once every 1.7 days and that they are about 40 light-sec apart, very close astronomically speaking! By measuring the velocity of the visible star in its orbit astronomers are able to determine that the unseen star must have a mass about 10 times greater than the sun's mass. Such a star, if it were a normal star, should be much brighter than the (normal) companion star that we do see. The only other explanation seems to be that this massive object is a black hole.

The gravitational pull of the unseen black hole on the visible star is so strong that the star is distorted into an egg shape. As we view this elongated star from different angles, as it moves through its orbit, its brightness appears to change. By measuring the exact amount of the variation in brightness an independent estimate of the mass of the black hole can be made. This value agrees very well with an estimate of 10 solar masses previously determined from the motion of the star.

The faint binary system first became interesting because of the strong x rays that it emits. Very few stars produce x rays; x rays usually indicate the presence of a collapsed and dying star. In this case, the black hole is pulling material off the surface of its visible companion star. As the gases are swirled down toward the black hole, they gain very high velocities and release intense x rays. LMC X-3 was examined during a study of the handful of stars emitting x rays in our neighbor galaxy, the Large Magellanic Cloud.

Eventually the strong gravity of the black hole will completely destroy the visible companion star which we now see. When that happens we will no longer have any way of detecting the black hole in LMC X-3. There could be many such isolated black holes in the universe, but we have no way to find them.

Anne Cowley, University of Michigan

1. Anne P. Cowley, Paper DC-3 presented at the Spring Meeting of The American Physical Society, Baltimore, Maryland, 18–21 April 1983.

Pulsars: The Fastest and the Farthest

Before this year, the most rapidly rotating celestial object was the pulsar located in the heart of the expanding gas cloud known as the Crab Nebula. The remnant of the supernova of 1054, it was also thought to be the youngest known neutron star and, therefore, the most rapid rotator among celestial collapsed objects. It has a period of 33 msec. Now that record has been spectacularly broken with the discovery of a pulsar, called PSR 1937 + 214, with a period of only 1.5 msec; its existence was not suspected and it raised serious and important questions concerning pulsar theory.

The millisecond pulsar, as it is called, was originally observed during a study of the radio source 4C21.53, which was noted as having a peculiar spectrum, somewhat characteristic of pulsars.[1,2] It had so short a period that it was missed during previous searches for pulsed radio emission, such as the survey which discovered the binary pulsars. Correcting for interstellar dispersion, the period was found to be 1.5578 msec.

Using the measured[3] period change, which is only about 10^{-19}, it is generally possible to derive an "age" for the pulsar, assuming that the emission of electromagnetic waves by the rotation of the magnetic field brakes the stellar rotation. This mechanism, which appears to work quite well for many of the observed pulsars, yields in this case a lower limit for the age of about 10^8 to 10^9 years, a result completely out of line with its measured space velocity and emission strength.

Clearly, this is a new type of pulsar, one which does not conform to the general pattern of behavior observed for most of the other known members of the class of collapsars. The discovery of the optical counterpart of the pulsar confirms the radio properties.[4] Furthermore, there appears to be no associated supernova remnant on the basis of x-ray observations.[5]

Several explanations have been advanced for the pulsar's behavior. The first explanation, that the neutron star was in a binary system and had "spun up" by accreting matter,[6] has been ruled out since the pulsar does not appear to be in a binary system.

Another explanation is that the pulsar's magnetic fields are unusually low.[7] Since the spindown of a pulsar is believed to be driven by magnetic dipole radiation and particle torquing, the weaker fields would not produce so rapid a braking and would give the star the appearance of youth. The pulsar, therefore, can preserve its rotational state, a remnant of the formation process, for a longer time. That the magnetic field should be several orders of magnitude weaker than for the average pulsar, may explain why these objects have not previously been detected—they are simply rotating too quickly for most surveys.

A second rapid pulsar, called PSR 1953 + 290, with a period of 6.1337 msec, has now been discovered.[8] Its position has been determined with the very large array (VLA) radio telescope to be near the gamma-ray source G065 + 1. Most unexpected is the fact that this neutron star *is* in a binary system. Having an approximately circular orbit, the period of the binary is 120 ± 4 days, much longer than previously known binary pulsar periods. It has an inferred semimajor axis of at least 10^8 km—far too wide for mass transfer to take place.

The recent discovery[9] of a radio pulsar in the Large Magellanic Cloud (LMC), the satellite galaxy near the Milky Way, not only extends our knowledge about neutron star formation but also aids distance determination to the LMC galaxy. The pulsar, designated PSR 0529 − 66, is not an accreting x-ray binary system and, therefore, can be directly compared with counterparts in our own galaxy. The pulse structure is that of a single emission peak, with a period of 0.9757 sec (similar to the first pulsar discovered in our galaxy, CP 1919 + 21). There is considerable variability in amplitude. A possible association may exist between the pulsar and a nearby hard x-ray source, about 8 arcmin away, but that is uncertain.

By using the dispersion measure for the signals generated by electrons in the galactic interstellar medium it is possible to state that the pulsar is indeed in the LMC. Once that is established it should be possible to use this pulsar as a peg upon which to hang the distance modulus to the Magellanic Clouds, an important quantity for cosmology. The fact that the pulsar is so similar to galactic objects reinforces the conviction that stellar evolution has proceeded in similar fashion in both our galaxy and the other members of the Local Group.

Steven Shore, Case Western Reserve University

1. D. Backer *et al.*, *IAU Circular 3743* (1982).
2. D. Backer *et al.*, Nature **300**, 615 (1982).
3. D. Backer *et al.*, Nature **301**, 314 (1983); M. Ashworth *et al.*, Nature **301**, 313 (1983).
4. R. N. Manchester *et al.*, *IAU Circular 3795* (1983).
5. R. H. Becker and D. J. Helfand, Nature **302**, 688 (1983).
6. M. A. Alphar *et al.*, Nature **300**, 728 (1982).
7. V. Boriakoff *et al.*, *IAU Circular 3806* (1983).
8. J. Arons, Nature **302**, 301 (1983); Phys. Today **36**, 19 (March 1983).
9. Nature **303**, 307 (1983).

The Void in Böotes

A deep survey of the distribution of galaxies in the northern sky confirms the existence of a giant void in intergalactic space nearly 350 million light-years across in which no galaxies are found. The new survey, carried out by Robert P. Kirshner of the University of Michigan, Augustus Oemler at Yale University, Paul Schechter and Stephen Schectman of the Mount Wilson and Las Campañas Observatories entailed measuring the distances to 231 galaxies spread over the northern sky in the direction of the constellation Böotes. In an earlier investigation (see *Physics News in 1982*, p. 14) the four observers had suggested that the Böotes region was missing galaxies over a vast range in depth.[1] The new survey covers the region in more detail by charting the three-dimensional positions of the galaxies in 282 small fields spanning the area on the sky thought to contain the Böotes void.

The new observations show that the void has the same direction, size, and distance indicated by the earlier, less extensive work. Nearby galaxies can be seen; distant galaxies can be seen; but in the void, there is nothing.

Astronomers are interested in the distribution of galaxies on the largest observable scales because that may provide a clue to the origin of galaxies and galaxy clustering. Galaxies and clusters are expected to form through gravitational attraction from fluctuations that were present in the distant past, not long after the Big Bang. By observing the present form of galaxy clustering, astronomers hope to learn more about the physical conditions in that early epoch.

It's a little like looking at fossils. Astronomers observe things which were made in the distant past. The void in Böotes is similar to those found in other surveys of galaxy positions but is much larger.

Located at a distance of about one billion light years, the diameter of the void is about 350 million light years, big enough to hold about 100 million galaxies as big as ours. Of course, galaxies are ordinarily separated by substantial distances. If the void region had the normal density of galaxies, it would hold about 10,000 of these vast stellar systems. The great size of this void makes it particularly interesting to compare with theoretical prediction of galaxy clustering.

The survey of the void was carried out at Kitt Peak National Observatory, Palomar Observatory, Las Campãnas Observatory,[2] The Multi-Mirror Telescope, and the McGraw–Hill Observatory. For each galaxy, the four astronomers measured its apparent brightness and the velocity at which it is receding from our galaxy. They used the resulting red shift as a measure of the distance in plotting the location of each galaxy in depth. The measurement of 231 red shifts revealed the presence of nearby galaxies and distant ones, but none in the Böotes void.

The void observed here is not big enough to shake confidence in the overall picture of a homogeneous universe, since the size of the void is only a few percent of the radius of the Universe. On the other hand, it is the largest possible structure that could have been detected in this survey. It is interesting to speculate whether deeper surveys will find structure in the universe on still larger scales.

Robert P. Kirshner, University of Michigan

1. R. P. Kirshner, A. Oelmer, P. L. Schecter, and S. A. Schectman, Astrophys. J. Lett. **248**, L57 (1981)
2. R. P. Kirshner, Paper EC-3 presented at the Spring Meeting of The American Physical Society, Baltimore, Maryland, 18–21 April 1983.

IRAS

The Infrared Astronomical Satellite IRAS was launched on 26 January 1983. A joint product of the United States, the United Kingdom, and The Netherlands, it marks the beginning of the space age for infrared astronomy, and the first time that this wavelength region has been accessible from space. Because infrared radiation is hampered by the Earth's atmosphere, infrared astronomers have been limited to a few very-high-altitude observatories.[1,2] With the exception of Mauna Kea, an extinct volcano in Hawaii with an altitude of some 4000 m, most observatories are so limited in infrared sensitivity that astronomers have been forced to resort to clever expedients to extract even a small bit of information from the infrared sky. The mission of IRAS is to perform an all-sky survey at wavelengths of 12, 25, 60, and 100 μm with a spatial resolution of better than 5′. The entire sky is covered every six months, with surveys at higher angular resolution also planned for particular regions.

The focal plane instruments in IRAS are cooled to 2.7°K by superfluid liquid He. Because the liquid helium evaporates, the lifetime of the satellite is limited to about 11 months in orbit. Several instruments function at the focal plane: an area survey multiwavelength spectrometer at each of the four chopped photometric channels, each with a field of view of 1.2′ and low-resolution spectrometers with diameters of 5.0 and 7.5′. About 60% of the operating time is spent in survey work while the rest is spent on pointing at specific objects.

Almost as soon as IRAS operations began, on 1 February, it has produced exciting results. IRAS has the distinction, for example, of being the first satellite to "discover" a comet, 1983D, now officially named IRAS-Alcock. This comet, which passed very close to the Earth and was therefore also extensively observed from the ground, should provide an important clue to the development of dusty comets in the inner solar system. Shortly thereafter, a second near-Earth comet was observed, which IRAS was also used to study. Since the International Ultraviolet Explorer (IUE) is also currently operational, astronomers have the unprecedented opportunity to observe simultaneously in the ultraviolet and infrared, the two wavelength regions most easily linked with ground-based visual observations.

IRAS has also produced the first infrared maps of M31, the spiral galaxy in Andromeda, and of the Large Magellanic Cloud, the satellite galaxy near our own. The M31 map shows that the strong neutral hydrogen emission (at 21 cm) and a ring of ionized hydrogen regions observed from the ground is coincident with a bright ring seen to be emitting in the far infrared—a mark of recent and continuing star formation. The entire map took 36 min to complete.

The M31 map also shows that the nucleus is a strong emitter at 60 and 100 μm, but not at 21 cm. The total IR luminosity of the galaxy is about 1% of the optical brightness, compared with about equal emissivities for our own galaxy. The LMC map clearly shows many sites of active star formation.

IRAS observations have also recently uncovered an infrared-emitting region in the vicinity of Vega, one of the brightest stars in the sky. The disk of dust particles emitting IR is interpreted by some as a solar system, about twice as large as our own, in the making around Vega.[3]

The catalog of all IRAS observations should be compiled by late 1984. However, to satisfy the enormous need and curiosity of the astronomical community, periodic IRAS catalog "fiches" have been issued at irregular intervals since the start of the observations. These will continue until the publication of the final catalog.

Steven Shore, Case Western Reserve University

1. Nature **303**, 287 (26 May 1983).
2. Science **220**, 1365 (24 June 1983).
3. New Scientist **99**, 455 (18 August 1983).

Dynamics of Large Systems of Galaxies

It has often been said that observational cosmology is the search for two numbers, the Hubble constant H_0, and the deceleration parameter q_0. Most observers now agree that the Hubble constant is somewhere between 50 and 100 in the units of km per sec per megaparsec (that is, 10 to 20 miles per sec per million light years).

The best current way of measuring the second parameter is by measuring the mean matter density of the universe. The deceleration or slowing of the expansion of the universe with time is directly related to the amount of matter and energy it contains—it is the combined gravitational pull of all the matter in the universe on itself. The actual method for measuring the matter density consists of measuring the number density and the masses of galaxies of different absolute brightness.

These numbers are usually called the luminosity density (measured in solar luminosities per unit volume of space) and the mean mass-to-light ratio (abbreviated M/L and also measured in solar units). Multiplying the luminosity density by the mean M/L gives you the mass density.

While the value of the Hubble constant is well known (an outstanding factor of 2 in this game is small!) and the luminosity density is well known (to within 10%), estimates of the mass-to-light ratio for galaxies range from a few (in solar units) to over 1000. In particular, these estimates have tended to increase with the scale of the galaxy systems measured, prompting early observers to postulate the existence of large amounts of "dark" matter that clumps weakly with galaxies—the so called "missing mass" problem. If these early estimates for the M/L of galaxies were extrapolated to sizes for galaxy systems only a factor of 2 or 3 larger than clusters of galaxies—i.e., to the size of superclusters—the derived mass density would be enough to "close" the universe. The universe would eventually collapse back upon itself in a "big crunch."

Recently, high-powered radio and optical techniques have increased our ability to measure very accurate radial velocities for galaxies.[1–7] Velocity measurements lie at the heart of all efforts to measure the masses of galaxies. Coupled with new statistical techniques for both the identification of groups of galaxies and the study of the richer clusters of galaxies, we have been able to make substantially improved estimates of the masses (and thus the M/L) of groups and clusters of galaxies. Such systems of galaxies range in size from a few hundred thousand light years up to several million light years.

In addition, a very powerful new tool has been developed for the measurement of distances to galaxies (the Infrared Tully–Fisher method) which now allows us to map out the distortion in the Hubble expansion of galaxies near our own galaxy owing to the presence of our own Local Supercluster of galaxies.[5] This provides us a mass estimate for matter clustered on a scale of almost 100 million light years!

These new measurements have given a surprising result. The mass-to-light ratio for systems of galaxies on scales of groups to superclusters is constant. There does not appear to be any large amount of dark matter clustered even on scales of superclusters. The derived M/L and thus the mean mass density from even the largest system fails to close the universe by a factor of 10.

Robert Frost once wrote "Some say the world will end in fire, some say ice..." It looks as if we have some chilly times ahead.

John P. Huchra, Harvard–Smithsonian Center for Astrophysics

1. J. Huchra and M. Geller, Astrophys. J. **257**, 423 (1982).
2. I. Gioia, M. Geller, J. Huchra, T. Maccacaro, J. Stocke, and J. Steiner, Astrophys. J. Lett. **255**, L17 (1982).
3. M. Davis and J. Huchra, Astrophys. J. **254**, 437 (1982).
4. T. Beers, J. Huchra, and M. Geller, Astrophys. J. **264**, 356 (1983).
5. A. Aaronson, J. Huchra, J. Mould, P. Schechter, and R. B. Tully, Astrophys. J. **258**, 64 (1982).
6. G. Bothun, M. Geller, T. Beers, and J. Huchra, Astrophys. J. (in press).
7. M. Geller and J. Huchra, Astrophys. J. Suppl. (in press).

What is the Cosmic X-Ray Background Telling Us About the Quasars Missing at High Red Shifts?

The distance to the farthest objects in the universe is measured in terms of Doppler red shift, the fractional shift in the wavelength of the light from the object owing to that object's cosmological recession. Red shift is denoted by the letter Z. There is now strong evidence that the increase in the space density of high-luminosity quasars with large "look-back time" (the light coming to us from quasars was emitted billions of years ago) does not persist beyond red shifts of 3.5.[1,2] The observation[3] of the radio-loud quasar PKS 2000-330 at $Z = 3.78$ as a strong source of optical lines indicates that various "seeing" effects (such as the obscuring effect of intergalactic dust) cannot readily explain the paucity of quasars at such high red shifts.[4]

We already know, however, that the power-law x-ray spectra of bright quasars[5] cannot be similar to the spectrum characteristic of those unresolved sources that dominate the extragalactic thermal x-ray background.[6] If these thermal-type sources of the cosmic x-ray background are indeed quasar-like objects, then recent photoexcitation calculations indicate that they would tend to be extremely weak in most of the atomic emissions usually associated with typical quasars.[7] This would suggest a pronounced spectral evaluation whereby young quasars with thermal x-ray emission and relatively weak optical lines eventually became nonthermal x-ray sources with strong optical lines.[8]

Correlation of data from observations made with the Space Telescope (scheduled for 1986) and with the proposed Advanced X-ray Astrophysics Facility (AXAF) should provide the information required for tracking the early stages of quasar evolution and should thereby help distinguish such spectral transitions from changes in space density or luminosity alone. In the meantime, further ground-based optical surveys with increased sensitivity should provide additional clues.

Elihu Boldt, Goddard Space Flight Center

1. P. Osmer, Astrophys. J. **253**, 28 (1982).
2. M. Schmidt and R. Green, Astrophys. J. **269**, 352 (1983).
3. B. Peterson, A.Savage, D. Jaucey, and A. Wright, Astrophys. J. **260**, L27 (1982).
4. J. Ostriker and L. Cowie, Astrophys. J. **243**, L127 (1981).
5. D. Worrall and F. Marshall, Astrophys. J. (in press).
6. G. DeZotti *et al.*, Astrophys. J. **253**, 47 (1982).
7. E. Boldt and D. Leiter, Astrophys. J. (to be published).
8. D. Leiter and E. Boldt, Astrophys. J. **260**, 1 (1982).

The Space Telescope

Many astrophysicists consider that the launch of the Space Telescope, in late 1986, will be the largest step forward in optical astronomy since Galileo's use of the first telescopes. The telescope, a 2.4-m reflector, will point to an accuracy of 0.007″ (7 milliarcsec) and achieve diffraction-limited images with an angular resolution of better than 0.1″. This is an order of magnitude improvement over the 1″ resolution imposed on ground-based telescopes by having to look through the earth's atmosphere. Space instruments can also observe ultraviolet and infrared wavelengths inaccessible from the ground. The magnesium fluoride coatings give high reflection down to near 1200 Å, allowing observation of the rich spectrum of atomic and molecular transitions present in the near ultraviolet.

The Space Telescope is intended to be a permanent facility which will be periodically refurbished and whose instrument complement will occasionally be updated or changed. The first set of detectors includes two cameras: (1) a wide field/planetary camera with a resolution of 0.043″ to 0.1″ and (2) a faint object camera with a smaller field of view but higher resolution (up to 0.022″). The initial detection package also includes a polarimeter and two spectrographs: the faint object spectrograph with spectral resolutions ($\lambda/\Delta\lambda$) of 100 to 1000 and the high-resolution spectrograph with resolutions of 2000 to 100,000. The wide field camera is expected to be the most heavily used instrument, but the faint object camera will be used for the highest resolution and deepest observations. The spectrometers will take advantage of the ultraviolet capability.

The most important discoveries will almost certainly be unexpected, as was Galileo's discovery of the moons of Jupiter. However, it is hoped that the instrument will tie down cosmological distance scales and determine the deceleration of the Hubble flow (deciding whether the universe is open or closed). It may also be possible to find planetary systems around nearby stars. The results of these two experiments alone will have profound effects on our philosophical view of the universe.

The Space Telescope is a guest investigator facility. It will be operated from Goddard Space Flight Center and from the newly formed Space Telescope Science Institute at Johns Hopkins in Baltimore.[1] The Institute will also serve to scientifically monitor the telescope and instruments, maintain data archives and analysis systems and run the organization of the guest investigator program.

Lennox Cowie, Space Telescope Science Institute

1. Science **221**, 249 (15 July 1983).

A Supermassive Compact Object at the Heart of the Most Luminous Object in the Universe

There is new evidence indicating that a supermassive compact object, a huge mass containing about 10 billion times as much mass as the sun, may be the powerhouse of one of the most powerful energy sources in the universe, a quasar-like BL Lacerta object called B2 1308 + 326. Astronomers at several institutions have observed the brightness of this object for the past seven years and detected outbursts of light from it that occur at intervals of approximately one year. The regularity of these outbursts is an indication that some kind of supermassive object—perhaps a giant black hole or a huge supermassive star—is the source of the energy that we see from these objects.

Astronomers have known for some time that powerful energy sources like B2 1308 + 326 exist in the universe, but it has been very hard to make measurements that tell us anything directly about the object that produces all this power. At the peak of the most recent outburst in early 1983, B2 1308 + 326 was thought to be the most luminous object in the universe at that time. The semiregular outbursts of light from B2 1308 + 326 are, according to Wayne Stein, among the first pieces of direct evidence that bear on the nature of the central energy generator of quasars.[1]

BL Lacerta objects like B2 1308 + 326 are closely related to the quasars, which were discovered in 1962. Quasars are star-like objects that almost certainly are billions of light years from Earth and are far more powerful energy sources than the nearby stars which they resemble. Stein refers to these BL Lacerta objects as "naked quasars," since most of the light from them comes directly from high-speed electrons emitted by the nucleus of a galaxy. In quasars, some light comes from low-density gas clouds surrounding the galactic nucleus, and consequently it can be harder to interpret measurements of radiation from a quasar. This light may obscure observation of the central energy source.[2]

Harry Shipman, University of Delaware

1. W. Stein, S. Mufson, and W. Wisniewski, Bull. AAS **15**, 671 (1983).
2. R. Wolstencroft, G. Gilmore, and P. M. Williams, Mon. Not. R. Astron. Soc. **201**, 479 (1982).

Artist's rendering of the Space Telescope, as deployed by the Space Shuttle.

Optical Transient Correlated to Gamma-Ray Bursts

Transient event optical astronomy may become a dynamic new field in astrophysics during the next few years. It was initiated two years ago with the discovery by B. Schaefer of the Massachusetts Institute of Technology of an archived photograph, taken in 1928, showing a star-like image exactly at the celestial location of a gamma-ray burst observed in 1978.[1,2] Analysis of the image argues for a variety of reasons for a brief optical flash, with a duration of seconds or minutes, that was as bright as the third magnitude and hence easily visible to the naked eye.

Since then Schaefer has found at least two more archived optical transients at the precise locations of gamma-ray bursts that were observed in 1979 (see *Physics News in 1980*, p. 13). These were also photographed many decades ago. Given the ratio of the total optical monitoring time (represented by the several thousand archived photographs that were searched) to the nearly one century of elapsed time sampled by the optical observers, one concludes that gamma-ray burst sources, presumably neutron stars, must emit visible optical transients fairly frequently, perhaps several times per year.

This hope has promoted the design and construction both of all-sky optical transient monitors, using CCD (charge-coupled device) arrays, and of a rapidly orienting telescope with a fractional-second response time. These instruments are being built by groups at MIT and at NASA Goddard, respectively, for intercepting, locating precisely, and photographing the transients during their occurrences. Not only will the optical time histories and repetition patterns thus be available for study, but the relationships of the optical transients to gamma-ray burst events detected with the Gamma Ray Observatory and the Solar Maximum Mission will provide a dramatic new interdisciplinary study. In this manner, we may well be able to observe the sources of gamma-ray bursts directly.

Thomas L. Cline, Goddard Space Flight Center

1. Natl. Geogr. **163**, 731 (June 1983).
2. B. Schaefer, Nature **294**, 722 (24 December 1981).

Quasar Fuzz and the Red Shift

The association of quasars with the nuclei of galaxies (see *Physics News in 1981*, p. 7) has been the object of much work during the past three years.[1] The advent of CCD (imaging using charge-coupled devices) has recently enabled astronomers to measure the red shifts of very faint objects. (The most distant normal galaxy, 3C324, with a red shift of 1.21, was found using a CCD.)[2] CCD detectors have also been used[3] in observations of the surrounding galaxies associated with a number of nearby quasars, those with red shifts less than $Z = 0.1$. The recent observation by Balick and Heckman[4] of the spectra of this fuzzy region in several quasars is, therefore, of great importance in pinning down the nature and origin of the active galaxies.

Balick and Heckman used a sample consisting of four quasars with red shifts ranging from 0.036 to 0.37. All four had been classified as quasars on the basis of both their optical emission-line spectra and their morphology (star-like appearance). Using the cryogenic camera and CCD on the 4-m telescope at Kitt Peak, Balick and Heckman succeeded in obtaining, at several slit orientations, the spectra of not only the active core regions, but also the spectra of the fuzz surrounding them. Clearly detected absorption lines, with the same red shift as the emission from the nucleus, confirmed that a quasar actually resided in a normal galaxy in each case. The absorption lines arose from A-type (intermediate mass) stars.

In one case, 3C48, the galaxy is an active radio source as well. This source was also studied by Boroson and Oke who succeeded in observing the Balmer absorption lines.[4] The clear identification of this source within a galaxy (one which itself appears somewhat more active than normal) further adds support to the picture that compact, relativistic objects in the nuclei of otherwise normal stellar systems are responsible for the quasar and Seyfert phenomena.

We can now be virtually certain that the red shifts observed in the quasars do indeed arise from the overall expansion of the Universe, and not from the operation of as yet unknown and exotic physical laws.

Steven Shore, Case Western Reserve University

1. S. Wyckoff, P. A. Wehinger, and T. Gehren, Astrophys. J. **247**, 250 (1981); S. Wyckoff, P. A. Wehinger, H. Spinrad, and A. Boksenberg, Astrophys. J. **240**, 25 (1980).
2. New Scientist **97**, 428 (17 February 1983).
3. J. B. Hutchings, B. Campbell, and D. Crampton, Astrophys. J. Lett. **261**, L23 (1982).
4. B. Balick and T. Heckman, Astrophys. J. Lett. **265**, L1 (1983); B. Balick, Mercury **12**, 81 (1983); T. A. Boroson and J. B. Oke, Nature **296**, 397 (1982).

The Quadrupole Anisotropy

The cosmic background radiation field observed primarily at microwave wavelengths has a rather good blackbody spectrum with a characteristic temperature of about 2.7 K. It is very isotropic and the combination of spectral shape and isotropy have led to the belief that this radiation is the remnant of the initial fireball or cosmic explosion out of which the Universe as we know it emerged.

Since 1965, many observations have been made to determine the degree of isotropy on varying angular scales with greater and greater sensitivity. During the last few years, there has finally emerged a consensus among observers that there is a small anisotropy in the radiation field amounting to about 3 mK and having an overall dipole angular distribution.[1] This is equivalent to saying that the Universe is a little warmer in the east and cooler in the west. This anistropy has been interpreted as being due to the net motion of the solar system through the background radiation field.

In fact, the dipole anistropy agrees quite well with the amplitude and direction one finds by measuring the combined motions of the sun within the Milky Way Galaxy, and of the Milky Way among the Local Group of galaxies. The sun appears to be moving with a velocity of about 372 km/sec in a direction defined by a right ascension of 11.2 h and a declination of $-6°$. This implies an overall motion of the Local Group of galaxies away from the Virgo cluster with a velocity of about 600 km/sec.

In addition to the steady dipole anisotropy there also appears to be an even smaller residual dipole anisotropy with an annual variation in amplitude of one year, consistent with the suspected motion of the Earth about the sun.

No cosmologically significant anisotropy has definitely been established on very small angular scales (1°–10°), again down to a level of sensitivity of about 0.1% of the total observed background flux.

In the past few years two groups have reported another large-scale anisotropy in the background radiation field over very large angular scales,[2,3] which they reported as an overall *quadrupole* anisotropy. If correct, such an anisotropy would imply that the Universe, rather than being essentially homogeneous and isotropic on the largest scales would instead possess a sort of ellipsoidal or football overall shape. Such a conclusion would also have dramatic consequences for other aspects of cosmology, such as the question of the formation of galaxies.

Now, however, two other groups[4,5] have made new observations of the background radiation field and find no evidence at all for a quadrupole anisotropy. Their results differ from the earlier ones primarily by the subtraction of the effects of the dipole anisotropy owing to our motion as well as the contributions from our own galactic plane, leaving essentially no large-scale residual anisotropy.

The universe seems smooth after all.

Kenneth Brecher, Boston University and Goddard Space Flight Center

1. Richard Muller, Sci. Am. **231**, 26 (August 1978).
2. R. Fabbri, I. Giuidi, F. Melchiorri, and V. Natale, Phys. Rev. Lett. **44**, 1563 (1980).
3. S. Boughn, E. Cheng, and D. T. Wilkinson, Astrophys. J. Lett. **243**, L113 (1981).
4. P. M. Lubin, G. L. Epstein, and G. F. Smoot, Phys. Rev. Lett. **50**, 616 (1983).
5. D. J. Fixsen, E. S. Cheng, and D. T. Wilkinson, Phys. Rev. Lett. **50**, 620 (1983).

Planetary Science Looks to the Future

In 1983, two important planetary science missions reached turning points. First, the Viking mission to Mars stopped returning data and ceased to respond to commands from the ground early in the year. Second, the Pioneer 10 mission, which flew by Jupiter in December 1973, left the solar system in June, continuing to gather information on the physical state of the remotest depths of space directly sampled by human technology.

At the same time, NASA's Solar System Exploration Committee (SSEC), releasing the first part of its report, called for a new approach to planetary exploration: a continuing, low-cost core program containing a wide variety of missions to various destinations. The SSEC report is, in a sense, complementary to the "Field Committee" report of the National Academy of Sciences' Astronomy Survey Committee, published last year (see *Physics News in 1982*, p. 9). The Field Comittee report, which focused on astronomy beyond the solar system, specifically excluded spacecraft exploration of the planets from its decisions.

Viking and Pioneer are survivors of an earlier era of planetary science when NASA budgets were less constrained and when spacecrafts were custom designed and rather complex. This approach succeeded spectacularly when we first began to explore worlds beyond our own, but it ran into obstacles when budgets became more restricted. The last spacecraft of this era, the Galileo probe to Jupiter, has suffered from repeated delays. In addition, the overall NASA support for planetary science declined, in constant dollars, to 20% of the peak support of the mid-1970s. The SSEC plans to cut costs by using spacecraft which, instead of being designed anew for each mission for doing the maximum conceivable amount of science, are reusable to the maximum extent. In the case of missions to the inner solar system, spacecraft can be adapted from existing Earth-orbiting satellites.

The first four missions recommended by the SSEC cover a wide variety of destinations. The Venus Radar Mapper (scheduled for a new start in Fiscal Year 1984) and the Mars Geoscience/Climatology Orbiter will permit surface mapping and detailed meteorological studies of two planets which are similar to, but also different from, the Earth, allowing us to understand the evolution of our own planet through comparative planetary studies. The third core mission, the Comet Rendezvous/Asteroid Flyby, requires the development of a Mariner Mark II spacecraft, a multipurpose probe that will play a central role in the further exploration of the outer solar system. The fourth high-priority core mission involves sending a modified version of the Galileo probe to Titan, the largest satellite of Saturn. Titan is the only object in the Solar System, other than the Earth, that has a thick atmosphere of nitrogen.

The SSEC's program extends beyond the four highest priority missions. The spacecraft used for these first four missions, or probes derived from Earth-orbiting satellites, will be used to probe three types of objects that exist in the solar system. The inner planets are the most similar to our Earth, and further probes to the moon, Mars, and Venus can tell us more about the evolution of our own planet. The small bodies—the asteroids and comets—have been untouched so far by NASA's space probes; studies of these objects, some of which are quite primitive, can tell us about the origin of the solar system and possibly about the resources available in near-Earth space (a new goal for planetary exploration identified by the SSEC). Finally, the outer planets—Saturn and Uranus fall within the SSEC's purview—are fundamentally different from the

Earth, and studies of them can tell us about fascinating, new types of worlds as well as illuminating the events that occurred while the solar system was being formed.

The SSEC's program addresses four major goals for solar system exploration. The primary goal of the planetary program continues to be the determination of the origin, evolution, and present state of the solar system. We also want to understand the Earth through comparative planetary studies and to understand the relationship between the chemical and physical evolution of the solar system and the appearance of life. The SSEC identified a new, secondary goal for solar system exploration: the survey of resources available in near-Earth space.

The SSEC's work continues. More ambitious missions, such as a sample return from Mars, a mobile lander that could explore the surface of Mars, and missions which would return the pristine fragments of a comet to Earth could produce fascinating science and generate the public enthusiasm associated with the Apollo, Viking, and Voyager missions. But the SSEC viewed the first priority as being the health of planetary exploration, which requires a program without wide budgetary swings. The Council of the American Astronomical Society, endorsing the SSEC report, called attention to the "particular need to establish a stable program in planetary sciences and to reestablish a critical level of flight activity." In the second part of its study, the SSEC will consider larger missions, which might be part of a more ambitious, better funded planetary program. However, in the view of the SSEC, these larger missions are second in priority to the establishment of a fundamental base for the planetary science program, a series of Planetary Observers comparable to the Physics and Astronomy Explorers which have been so successful.

Harry Shipman, University of Delaware

1. "Planetary Exploration through the Year 2000: A Core Program," Solar System Exploration Committee of the NASA Advisory Council, U. S. Government Printing Office.
2. David Morrison and Noel Hinners, Science **220**, 561 (6 May 1983).
3. J. Kelly Beatty, Sky and Telescope **65**, 116 (February 1983).
4. C. Covault, Aviat. Week Space Technol. (18 April 1983).

The Eclipse of Epsilon Aurigae

Astronomers are following the progress of a unique eclipse that occurs once every 27.1 years. The present eclipse began in July 1982 and became total in December 1982. Totality should last until January 1984, and the eclipse will end in May 1984.

What is unique about this eclipse? We cannot tell what the *eclipsing object* is. What's more, although it has been proven that the eclipsed object, a white supergiant star called epsilon Aurigae A, has been totally eclipsed since December 1982, astronomers still detect its spectrum, and its apparent brightness at the Earth has decreased by only a factor of 2.

In fact, these problems have mostly been with us since an eclipse of epsilon Aurigae A was first studied in 1901.[1] Techniques have improved with time, so that better data were taken at the eclipse of 1928–1930 and still more sophisticated measurements at the eclipse of 1955–1957, but investigators cannot agree on the nature of the eclipsing object.

The eclipsing object is very large compared to the diameter of the supergiant star that it eclipses, measured in the orbital plane of the epsilon Aurigae binary system.[2] That is why total eclipse lasts so long (about 13 months). But it was thought until recently that the eclipsing object was smaller than the supergiant star in the dimension perpendicular to the orbital plane. That would explain why we continue to observe the supergiant's spectrum throughout an eclipse. Observations of the present eclipse, however, made from the Pine Mountain Observatory of the University of Oregon show that the eclipsing object does block the whole supergiant star and thus must be partially transparent, allowing half the light to pass through.

In the case of epsilon Aurigae, we receive no visible light from the eclipsing object, which is one of its mysteries. Thus if there is a total eclipse and only one small region of the supergiant star shines unocculted as seen from Earth, a notable increase in polarization should occur just before totality. Exactly this effect was seen by the Pine Mountain Observatory[3] in December 1982. The implication is that the eclipse is total but that the eclipsing object is partially transparent.

What is the eclipsing object? Astrophysicists agree that it consists, at least in part, of a huge cloud of matter that accounts for most, if not all, of the eclipse. They differ on the composition of the cloud and on what lies at its center. Some think the cloud has a neutral transparency, like a photographer's neutral density filter, because the visible light is reduced equally at different wavelengths (colors) from the inception of the eclipse through totality; it is as though a thicker and thicker neutral density filter were passing in front of epsilon Aurigae A. Possible explanations: a cloud of dust (microscopic rock or carbon particles), with typical dust grain sizes larger than the wavelength of light—unlike ordinary interstellar dust whose grain sizes are smaller than the wavelength—or a thoroughly ionized gas.

The problem with the dust theory is that interstellar dust is usually accompanied by interstellar gas, yet no strong absorption lines ascribable to gas occur—as they should—during the eclipse of epsilon Aurigae A. A difficulty with the plasma theory is that such plasmas in space generally glow with light of their own and, hence, emission lines from the cloud should be seen during an eclipse, but none have been found. Further, what would keep the alleged plasma ionized? Some astronomers say there is a hot star at the center of the eclipsing cloud, which would ionize the plasma, and that they have detected continuum emissions from the star during the present eclipse with NASA's satellite observatory, the *International Ultraviolet Explorer* (IUE).[4] Other IUE observers, however, find no such emissions, but do find that in ultraviolet light the eclipsing region is not neutral, but blocks the shorter ultraviolet waves more than the longer waves.[5] This finding too needs confirmation. Of course, the different groups have observed at different times during the long eclipse and may be sampling different characteristics of the eclipsing object from one time to another .

If present studies with IUE and ground-based telescopes do not solve the problem of the eclipsing object in the epsilon Aurigae system, astronomers may have to wait for the eclipse of 2009.

Stephen Maran, Goddard Space Flight Center

1. Heather Cooper, New Scientist **95**, 762 (16 September 1982).
2. K. Gyldenkerne, Vistas Astron. **12**, 199 (1970).
3. J. C. Kemp, G. D.Henson, and D. E. Krauss, Epsilon Aurigae Campaign Newsletter, No. 6, 11 (February 1983).
4. M. Hack and P. L. Selvelli, Nature **276**, 376 (1978).
5. R. D. Chapman, Y. Kondo, and R. E. Stencel, Astrophys. J. **269**, L17 (1983).

Neutrons and Gamma Rays from Solar Flares

Acceleration of charged particles such as protons, nuclei, and electrons is a phenomenon that takes place routinely in nature. Evidence for this acceleration can be found in the direct detection of relativistic particles such as the cosmic rays, as well as by remote sensing via a variety of electromagnetic radiations such as gamma rays, x rays, and radio emission. The discovery of energetic neutrons from solar flares with the Gamma Ray Experiment on the Solar Maximum Mission (SMM) has added a new channel of remote sensing.[1] When combined with gamma-ray and other data, the neutron observations provide unique information on the particle acceleration process in solar flares.

The principal neutron production mechanism in flares is thought to be the breakup of helium and heavier nuclei in nuclear interactions of flare-accelerated particles in the solar atmosphere. The resultant neutrons have energies which reflect the energies of the primary charged particles, ranging from around 20 MeV up to perhaps 1 GeV. While neutrons of the highest energies survive the sun–Earth transit easily, a large fraction of the neutrons below about 50 MeV decay before they reach the Earth.

Neutron production in solar flares is accompanied by the production of nuclear gamma radiation. A variety of lines are produced, such as the very strong line at 2.223 MeV from neutron capture in the photosphere, as well as many other lines resulting from the deexcitation of nuclear levels. These lines have been seen from a variety of flares.

Solar neutrons have so far been observed from two flares, one occurring in 1980 and the other in 1982. Both of these flares were very impulsive in that their duration, less than a minute, was much shorter than the neutron transit time from the sun to Earth. As a consequence, the observed time profile of the neutron flux on Earth gives a time-of-flight measurement of the neutron energy spectrum at the sun.[2] Using the calculation based on laboratory measurements of neutron production cross sections, it is possible to reconstruct the energy spectrum of the accelerated particles. The resultant spectrum, defined over the energy range from about 100 MeV to to about 1 GeV, complements the information obtained from gamma-ray line ratios, which define the spectrum from about 10 to 100 MeV.

The overall spectrum was found to be consistent with the predictions of at least one acceleration mechanism, stochastic Fermi acceleration, although other mechanisms, in particular shock acceleration, could also yield the required spectrum. Another constraint on the acceleration mechanism is the rapid acceleration time set by both the neutron observations and the gamma-ray observations. These measurements indicate that the energetic particle spectrum, in at least some flares, is formed on very short time scales, on the order of a few seconds or less.

Reuven Ramaty, Goddard Space Flight Center

1. E. L. Chupp, D. J. Forrest, J. M. Ryan, J. Heslin, C. Reppin, K. Pinkau, G. Hanbach, E. Reger, and G. H. Share, Astrophys. J. **263**, L95 (1982).
2. Sci. News **123**, 53 (22 January 1983).

SETI

SETI, the Search for Extraterrestrial Intelligence, has long been an area of polite, and occasionally heated, debate.[1] Until recently, however, there has been no firm commitment of any substantial block of time to a systematic search for signals from life elsewhere in the universe. Now, with the development of several automated techniques for signal acquisition and processing using microprocessors, the field has taken on a new look and the arguments have moved from merely speculating on probabilities to actual debates over optimal search strategies.[2]

The first searches were conducted by Frank Drake in 1960. Under the name Project Ozma, observations were made for a comparatively brief time at a few nearby sun-like stars in an attempt to receive some artificially produced signal. Although unsuccessful, the search signaled the first serious discussion as to why there had been no detection when the probabilities at first appeared so high. Since then, there have been several analogous searches, always bootlegged off of other projects, always for only short spans of observing time.

The two systems which have changed this are the development of the so-called "suitcase SETI" by Paul Horowitz[3] at Harvard and the "parasitic" SETI system by Bowyer, Tarter, Zeitlin, Lampton, and Welch.[4] Both of these systems will have the capability of searching large numbers of objects for long trains of signals. Only the strategies differ.

Horowitz has begun observations using the 84-ft radio telescope, built originally by Smithsonian Astrophysical Observatory and Harvard for a 1420-MHz neutral hydrogen survey of the galaxy, but which has since been lying dormant. The necessary funds were provided by the Planetary Society in answer to a cutoff of federal funds for such efforts. The survey of the entire sky accessible from Massachusetts, between -30 and $+60°$, will take about six months at each selected frequency. The telescope, employed as a meridian instrument, intercepts about 0.5° of declination. The primary operating frequencies are all centered at about 1400 to 1700 MHz, the "water hole," so named because of its association with the spectral emissions by the constituents of water, H, and OH. The optimum window, when consideration is taken of galactic emission, atmospheric extinction, and even the microwave blackbody background radiation, is between 1 and 10 GHz. Horowitz's system uses 65,536 channels in a 2-kHz bandwidth.

The parasitic SETI system SERENDIP is designed to work off of whatever signal is being received. In particular, it will tap onto the Hat Creek Radio Observatory for about 35 days each year, integrating on whatever objects are being surveyed. The disadvantage is that it is constrained to observe whatever the telescope happens to be pointed at; on the other hand, in this mode it can operate as a random survey of the sky.

NASA is planning a Fourier-transform spectrum analyzer (FTA) which will sample 74,000 channels with bandwidths of 1 Hz; the FTA can also sample broadband (32 to 1024 Hz) signals. The system will be tested for the next five years on NASA's Deep Space Network (DSN) and at Arecibo, the world's largest radio telescope, in Puerto Rico. The eventual plan is to use the DSN telescopes at Goldstone, California and Tidbinbilla, Australia (already used for pulsar surveys) whenever the system is not employed in tracking interplanetary probes. The plan is to use about half the time to survey the sky in 32-Hz intervals from 1 to 10 GHz, estimated to take about three years, and the other part of the time to look at about 800 solar-type stars between 1 and 3 GHz.

Another telescope to enter the picture is the Ohio State University radio survey telescope. Originally used for observations of celestial continuum radio emitters, this instrument will be converted into a SETI telescope. Recent public support and scientific statements have saved the instrument from conversion into a portion of the golf course which borders it.

Finally, the International Astronomical Union has created a new commission dealing with the subject of SETI. The new commission is headed by Pappiagnis, Drake, and Kardashev, all leaders in the struggle to get the scientific community interested in the project.

Steven Shore, Case Western Reserve University

1. Leonard Ornstein, Phys. Today **35**, 27 (March 1982).
2. *The Search for Extraterrestrial Intelligence*, edited by P. Morrison, J. Billingham, and J. Wolf (Dover, New York, 1979); D. Goldsmith and T. Owen, *The Search for Life in the Universe* (Benjamin, New York, 1980).
3. Sky and Telescope **65**, 411 (May 1983).
4. S. Bowyer *et al.*, Icarus **53**, 147 (1983).

The radio telescope at Arecibo, Puerto Rico is sometimes used for SETI research. This figure shows the receiving antenna poised high above the 1000-ft.-diameter dish out of sight in the valley below. Photo courtesy of Cornell University.

CONDENSED MATTER

Condensed matter physics is a vast field which includes solid-state physics and the physics of quantum fluids such as the liquid heliums. Recent developments in this field may be loosely grouped into new phenomena, new materials, and new devices. Activity in recent years on topics such as localization, solid-state turbulence, two-dimensional phase transitions, and the quantum Hall effect continues vigorously. The latest and perhaps most interesting aspect of the quantum Hall effect will be described in more detail below.

The idea of "elementary excitations" is one of the unifying concepts of condensed matter physics and is analogous to that of "particles" in particle physics. One of the oldest elementary excitations is the "phonon," a collective mode whose properties in a given material are very revealing of the structure and forces at work in that material. Phonon physics is a lively branch of condensed matter physics and is represented below with a discussion of phonon imaging. The richest groups of elementary excitations are probably those found in liquid crystals and in the superfluid phases of liquid ^{3}He. We discuss below some aspects of the collective modes in the latter system that are surprisingly atomlike.

Tunneling is an important manifestation of quantum-mechanical behavior and is found in nuclei, molecules, crystals, and many-electron systems such as superconducting junctions and, perhaps, in nonlinear one-dimensional conductors. Tunneling on a macroscopic scale presents on the one hand conceptual problems associated with the foundations of quantum mechanics and on the other hand useful behavior that may be incorporated into devices such as superconducting transistors. At a finer level, tunneling now allows the production of images of surfaces on an atomic scale.

Synchrotron radiation continues to be an extremely important source of ultraviolet and x-ray photons for experimental condensed matter physics. Some of the latest developments make use of the short-time structure of the Cornell synchrotron to perform x-ray diffraction measurements with nanosecond time resolution. Other new large-scale facilities now having an impact on condensed matter physics include the small-angle neutron scattering facility at Oak Ridge National Laboratory and the intense pulsed neutron source at Argonne National Laboratory.

Materials science overlaps solid-state physics and continually provides new materials to study and new phenomena to explain. Artificially layered crystals grown by several epitaxial techniques are providing samples of semiconductors and metals with some properties that can be varied almost at will. Semiconductor physics and solid-state electronics are two fields currently profiting by the availability of semiconductor superlattices and heterostructures; nevertheless, the more straightforward technique of deliberately doping crystals with impurities continues to produce materials with fascinating and useful properties. Two examples are discussed in more detail below, namely dilute magnetic semiconductors, and the old field of color centers that is now very exciting, in part, because of color center lasers.

Miles Klein, University of Illinois

Fractional Quantum Hall Effect

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 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 (*Physics News in 1982*, p. 41).

New experiments show that the Hall conductance can be fractionally charged. That is, the conductance has been seen to possess third-integral (e.g., $\frac{1}{3}$ and $\frac{2}{3}$) multiples of the ratio e^2/h in addition to the usual integral values. The fractional quantum effect was discovered at temperatures below 2° K.[1] This phenomenon is the manifestation of a new state of matter—a two-dimensional quantum fluid of electrons, whose excitations are fractionally charged quasiparticles.[2]

This novel effect was realized in a new semiconductor thin-film structure, called a modulation-doped heterojunction.[3] The structure, which consists of a gallium arsenide (GaAs) crystal of exceptional purity and an aluminum gallium arsenide (AlGaAs) crystal selectively doped with donor impurities, is synthesized by using the highly sophisticated techniques of molecular beam epitaxy.[4] Owing to the difference in the energy band structure of the two semiconductors, the electrons given up by the donor impurities placed inside the AlGaAs crystal are confined in the GaAs crystal to the interface between the two semiconductors. These electrons are quantum-mechanically bound to the interface and free only in the plane of the interface. To a large extent, they behave as an ideal two-dimensional electron gas.

In the presence of a magnetic field, the behavior of a two-dimensional electron gas differs considerably from that of an ordinary gas in that the electrons experience the Lorenz force, the force of the crossed electric and magnetic fields and, as a result, execute a cyclotron motion in the magnetic field. The two-dimensional electron gas also differs from a three-dimensional electron system in that for three dimensions the electrons are free to move along the field direction and are thus allowed to take up a continuum of states. In the two-dimensional gas, the electrons lack freedom in the third dimension and the in-plane energy associated with the cyclotron motion is quantized. Consequently, the energies of the allowed states are a series of discrete levels, called Landau levels, each separated from its neighboring levels by the cyclotron energy of the electron. This singular nature of the energy structure is responsible for the many unusual electrical properties not found in usual three-dimensional systems.[5]

This independent electron picture does not take into account two important effects in real two-dimensional systems. It neglects the effect of disorder, such as interfacial defects and impurities unavoidable in real crystals, and the effect of Coulomb interactions among the electrons. The importance of disorder is most clearly demonstrated in the integral quantum Hall effect discovered three years ago.[6] The Hall conductance for that case exhibited flat plateaus quantized in integral multiples of e^2/h, the integral quantum number being identified with the number of completely filled Landau levels. The width of the plateau was related to the number of localized states caused by disorder.

The fractional quantum Hall effect, in contrast, is observed in systems with exceptional interfacial perfection and minimal impurities, and in the magnetic field limit where the lowest Landau level is fractionally occupied. The Hall conductance is quantized in fractional multiples of e^2/h; so far, only odd fractions with values $\frac{1}{3}$, $\frac{2}{3}$, $\frac{4}{3}$, $\frac{5}{3}$, $\frac{2}{5}$, $\frac{3}{5}$, $\frac{4}{5}$, and $\frac{2}{7}$ have been observed.[7] In the case of the $\frac{1}{3}$ and $\frac{2}{3}$ quantizations, the fraction is shown to be exact to better than one part in 10^4. These experimental observations suggest the condensation of the two-dimensional electron gas into a new state of matter owing to the Coulomb interaction among the electrons.

Very recently, theoretical calculations have demonstrated that the new electronic state was not an electron "solid," as was originally suggested. The ground state at odd fractional fillings of the lowest Landau level is an incompressible quantum fluid, separated by an energy gap from its excitations, which are fractionally charged quasiparticles.[2,8]

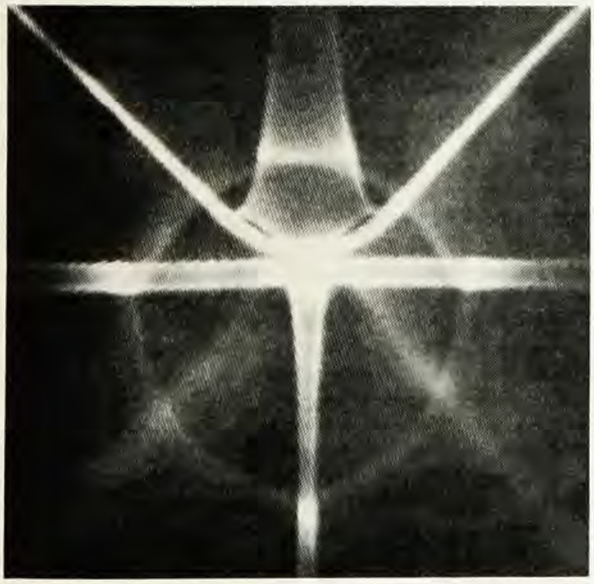
D. C. Tsui, Princeton and H. L. Störmer, Bell Laboratories

1. D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
2. R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
3. H. L. Störmer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. **29**, 705 (1979).
4. A.Y. Cho and J. R. Arthur, Prog. Solid State Chem. **10**, 157 (1975).
5. T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
6. K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
7. H. L. Störmer, A. M. Chang, D. C. Tsui, J. C. M. Hwang, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **50**, 1953 (1983).
8. Phys. Today **36**, 19 (July 1983).

Phonon Imaging

The transport of heat through crystals at liquid-helium temperatures affords some striking phenomena not witnessed at normal temperatures. Phonons, the dominant carriers of heat in nonmetallic solids, are (at sufficiently low temperatures) able to travel macroscopic distances without being scattered. Under these circumstances, heat does not flow in the familiar diffusive manner; it propagates ballistically. Thus, one can observe heat pulses passing through a medium at the velocity of sound and with little change in shape.

This ballistic property has been put to use recently in a series of beautiful phonon-imaging experiments that reveal the complex character of phonon propagation in crystals.[1–3] In one approach, a small superconducting bolometer, located at a fixed point on one face of a crystal, is used as a phonon detector. Heat pulses are generated in the opposite face by means of a focused laser[1] or electron beam[3] which is scanned across that face. The resulting two-dimensional images—one for sapphire (Al_2O_3) is shown in the accompanying figure—exhibit an extraordinary amount of structure. Complex patterns such as these occur even for crystals such as diamond, in which the velocity of sound is fairly isotropic. The sharpest features in this structure are called caustics.[4] The origin of this phenomenon—known as phonon focusing—is simply the elastic anisotropy of the crystal, which causes ray vectors for different phonons to be coincident.[5] Many of the patterns that occur in phonon images such as the fold, cusp, and hyperbolic-shaped curve that appear in the figure, are also encountered in the caustics of optical systems and electron beams. More recently, some other sharp but nonsingular features have been observed which are intrinsic to the crystal surfaces where the phonons are generated and detected.[6] These are providing important clues to the long-standing problems of phonon-boundary scattering.



This three-dimensional scanning tunneling microscopy image of a silicon surface is actually a photograph of an enlarged model of the surface that was assembled from individual two-dimensional contour scans. The photograph clearly shows two rhomboid-shaped unit cells. Hills and valleys within the unit cells are separated vertically at most by the equivalent of 2.8 Å. The individual hills or bumps, as little as 6 Å apart, have never before been observed.

In the wider context, ideas emerging from phonon-imaging investigations have helped to explain the shape of electron–hole droplet clouds in germanium[7] and have been exploited, for example, in the study of phonon–dislocation interactions[8] and phonon confinement in hot spots.[9] The field is still in its infancy, and one can look forward to a period of fruitful development and to a variety of further applications.

A. G. Every and J. P. Wolfe, University of Illinois

1. J. P. Wolfe, Phys. Today **33**, 44 (December 1980); G. A. Northrop and J. P. Wolfe, Phys. Rev. B **22**, 6196 (1980).
2. W. Eisenmenger, J. Phys. (Paris) Colloq. **C6**, 201 (1981).
3. R. Eichele, R. P. Heubener, and H. Seifert, Z. Phys. B **48**, 89 (1982).
4. J. C. Hensel and R. C. Dynes, Phys. Rev. Lett. **43**, 1033 (1979); P. Taborek and D. L. Goodstein, Phys. Rev. B **22**, 1550 (1980).
5. B. Taylor, H. J. Maris, and C. Elbaum, Phys. Rev. B **3**, 1462 (1971); A. G. Every, *ibid.* **24**, 3456 (1981).
6. G. L. Koos, A. G. Every, G. A. Northrop, and J. P. Wolfe, Phys. Rev. Lett. **51**, 276 (1983).
7. J. P. Wolfe, Phys. Today **35**, 2 (March 1982).
8. G. A. Northrop, E. J. Cotts, A. C. Anderson, and J. P. Wolfe, Phys. Rev. Lett. **49**, 54 (1982).
9. J. C. Hensel and R. C. Dynes, Phys. Rev. Lett. **39**, 196 (1979); M. Greenstein, M. A. Tamor, and J. P. Wolfe, Phys. Rev. B **26**, 5604 (1982).

Macroscopic Quantum Tunneling

A perennial paradox in quantum mechanics has been the idea that under appropriate circumstances a microscopic system such as an electron cannot be said to "be" in a definite state until it interacts with a measuring apparatus and is detected to be so; rather, until then it must be described as being in a "linear superposition" of two or more different states and only chooses between them, as it were, when it is observed. By means of a suitable experimental arrangement, it is possible to amplify this feature to the macroscopic level, that is, to arrange a situation in which a *macroscopic* object must, in principle, likewise be described by a linear superposition of states, corresponding in general to macroscopically different properties. In the past, however, this possibility has not been a major source of worry to most physicists, because it has been commonly assumed that there is no way of telling that the macroscopic body is in fact described by a superposition rather than "actually being" in one state or the other with some appropriate probability; the two descriptions were thought to have identical experimental consequences.

In the last few years it has become clear that the existence of superpositions of macroscopically different states can be tested, at least indirectly, by experiment. Most of the relevant experiments have been done on Josephson junctions, either biased by a fixed external current or incorporated in a single-junction superconducting quantum interference device (SQUID); in the first case, the relevant macroscopic variable is the phase of the wave function of the superconducting electron pairs; in the second it is the magnetic flux through the device. In either case one looks for evidence of superposition of states corresponding to widely different values of the variable in question. (A similar situation may arise[1] in some one-dimensional metals, where an analogous role is played by the phase of the charge density waves which exist in these metals.)

Although in principle various types of experiments are possible, the ones which are easiest to interpret have exploited the phenomenon of "macroscopic quantum tunneling," that is, the macroscopic analog of the decay of a heavy nucleus by emission of an alpha particle. In such a process, the macroscopic variable (e.g., the magnetic flux in a SQUID) initially possesses a value corresponding to a metastable minimum of the potential energy associated with it, and then escapes to a region of lower energy by tunneling through a region which would, in classical mechanics, be forbidden to it by a conservation of energy. The observation of such a phenomenon would constitute indirect evidence for the legitimacy of the idea of superposition of states corresponding to macroscopically different properties.[2]

There have been a number of experiments[3,4] which have looked for macroscopic quantum tunneling or related phenomena in Josephson systems; the most extensive are those of Voss and Webb at IBM.[4] They used all-nobium point contact junctions biased by a fixed external current and were able to take data down to temperatures as low as 3 mK. The comparison of the results with the theoretical predictions is complicated by the presence of dissipation in the junctions.[5]

Such dissipation tends to depress the rate of tunneling, but not necessarily to the extent of making it unobservable. The experimental results of Voss and Webb are in qualitative agreement with the theory, and in particular show a tunneling rate lower than that calculated neglecting dissipation. There remain some quantitative discrepancies which at present are not completely understood. If these results can be confirmed and extended, they will provide a firmer base than has previously existed for the hypothesis of superposition of macroscopically different states. Conversely, if the experiments do not show the theoretically predicted behavior, we might have to reexamine the assumption that quantum mechanics can be extrapolated from the microscopic to the macroscopic level in this way.

A. J. Leggett, University of Sussex

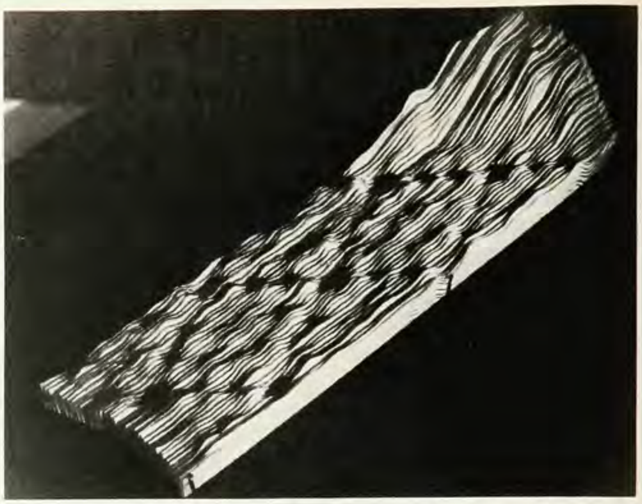
1. J. Bardeen, Phys. Rev. Lett. **42**, 1498 (1979).
2. A. J. Leggett, Prog. Theor. Phys. (Kyoto) Suppl. No. **69**, 80 (1980).
3. W. de Boer and R. de Bruyn Ouboter, Physica B and C **98**, 185 (1980); R. J. Prance *et al.*, Nature **289**, 543 (1981); L. D. Jackel *et al.*, Phys. Rev. Lett. **47**, 697 (1981); R. de Bruyn Ouboter and D. Bol, Physica B **112**, 15 (1982); I. M. Dmitrenko, G. M. Tsoi, and V. I. Shnyrhov, Fiz. Nizk. Temp. **8**, 660 (1982), translation in Sov. J. Low Temp. Phys. **8**, 330 (1982); D. Bol, R. van Weelderen, and R. de Bruyn Ouboter, preprint.
4. R. F. Voss and R. A. Webb, Phys. Rev. Lett. **47**, 265 (1981).
5. A. O. Caldeira and A. J. Leggett, Phys. Rev. Lett. **46**, 211 (1981); Ann. Phys. (NY), September 1983; V. Ambegaokar, U. Eckern, and G. Schön, Phys. Rev. Lett. **48**, 1745 (1982); G. Zwerger, Z. Phys. B **47**, 129 (1982).

Three-Dimensional Atomic Images of Surfaces

Three-dimensional images of solid surfaces that show unprecendented atomic-scale detail are now possible thanks to a powerful new technique developed at the IBM Zurich Research Laboratory. Called scanning tunneling microscopy, the technique makes use of the phenomenon of vacuum tunneling, in which electrons can pass between two conducting electrodes that are separated by a vacuum region only a few angstroms wide.[1]

The scanning tunneling microscope (STM) takes advantage of a particular property of the tunnel current: the strong dependence of such current on the separation between the electrodes. In fact, a reduction in separation distance equal to the diameter of a single atom produces a change in tunnel current by a factor of a thousand.

In the STM, a metal tip and the surface being studied serve as the electrodes. As the tip is moved, or scanned, laterally across the surface while separated from it by about 10 Å (one billionth of a meter), the tunnel current will vary in accordance with changes in the tip-to-surface distance. That tunnel-current variation is in effect a measure of the surface topography. In practice, the vertical position of the probe tip is changed to keep the tunnel current, and thus the tip-to-surface distance, constant for all points. In that way, monitoring the position of the tip while scanning yields a topographic picture of the surface.



An experimental phonon image for sapphire (Al_2O_3) at 1.6 °K made by scanning a laser beam across a metallized face of the crystal and detecting the resultant phonons at the opposite face. Bright regions indicate directions of high phonon flux in the crystal. The angular field of view is $\sim \pm 38°$ in the horizontal and vertical directions. The figure was obtained by G. L. Koos, A. G. Every, G. A. Northrop, and J. P. Wolfe at the University of Illinois.

Vertical resolution, an indication of the ability to resolve surface features in the vertical direction, is determined by the stability of the tip-to-sample separations. Using a two-stage spring system and other measures to suppress vibration, the researchers achieve a stability—and, hence, vertical resolution—of 0.1 Å, far beyond that of any other microscope. Lateral resolution is determined by the sharpness of the surface features on the tip. Under very special conditions, some other microscope techniques can provide somewhat higher lateral resolution. Such conditions include, for example, very thin samples and periodic sample structure. STM requires none of these and, furthermore, provides both high vertical *and* lateral resolution, but STM is best understood to be a complement to other techniques rather than a competitor. A field-emission version of the STM has been operated,[2] but owing to the large distance between tip and surface (hundreds of angstroms), the lateral and vertical resolutions were poorer in this case by nearly a factor of a thousand.

The tunneling current is not merely a function of the separation of the electrodes, but also of their work functions. This also makes the STM a very promising tool for surface chemistry on an atomic scale.[3]

The surface structure of silicon is an example of a problem that has intrigued scientists for many years. That STM has resolved individual silicon surface features less than 6 Å apart can be seen in the accompanying photograph, which shows two unit cells, the basic repeating crystallographic configuration of surface atoms.[4] Within each rhomboid-shaped cell are 12 clearly resolved, bumplike features that have never before been observed. The picture, according to the IBM researchers, eliminates most of the theoretical models of the structure that have been proposed even though some of the details regarding the interpretation of these bumps are not yet clear.

The surface structure of gold is another example for which STM has provided valuable information.[5] A number of theoretical models have been proposed to explain various, sometimes apparently conflicting, experimental results. By imaging the surface topography, STM enabled the researchers to confirm an atomic model that appears to explain all observed features in terms of a common underlying mechanism, namely, the spontaneous formation of ribbonlike facets. The resulting jagged surface is apparently more stable than a simple truncation of the bulk material.

Surface topography is only the first and perhaps the simplest application of this new, high-resolution, nondestructive technique. Possible future applications include: studies of electron properties of surfaces; the structure of adsorbates and biomolecules; the growth, structure, and electrical properties of thin overlayers such as oxides; the imaging of magnetic structures; and the study of fundamental problems in tunneling. A most important point for the evolution of the technique will be the understanding of tunneling in small nonplanar geometries for which very promising results have already been obtained.[6]

G. Present, IBM

1. G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Appl. Phys. Lett. **40**, 178 (1982); Physica B **109** and **110**, 2075 (1982); Phys. Today **35**, 21 (April 1982).
2. R. D. Young, J. Ward, and F. Scire, Rev. Sci. Instrum. **43**, 999 (1972).
3. G. Binnig and H. Rohrer, Surf. Sci. **126**, 236 (1983).
4. G. Binnig and H. Rohrer, Ch. Gerber, and E. Weibel, Phys. Rev. Lett. **50**, 120 (1983).
5. G. Binnig and H. Rohrer, Ch. Gerber, and E. Weibel, Surf. Sci. Lett. (in press).
6. A. Baratoff, 3rd Conference of the Condensed Matter Division of the EPS, Lausanne, 1983; J. Tersoff and D. R. Hamann, Phys. Rev. Lett. **50**, 1998 (1983); N. Garcia, C. Ocal, and F. Flores, *ibid.* **50**, 2002 (1983).

Collective Modes in Superfluid ^{3}He

There are in nature several kinds of superfluids, including the superconducting electrons in metals, the helium liquids (both ^{4}He and the rare isotope ^{3}He), and possibly the fluid interior of a neutron star. In many respects, the superfluid state is the most interesting of all the thermodynamic phases of matter. The superconducting property of metals (complete loss of electrical resistivity) is by now relatively well known; indeed, superconductivity may have an important role in computer operation, power transmission or, in general, the operation of any system employing large magnets, such as accelerators, power generators, or levitation magnets.

The superfluid helium liquids,[1] particularly ^{3}He, are less well known. From a theoretical standpoint ^{3}He is quite possibly the most interesting liquid in nature, for reasons which we shall discuss shortly. However, the liquid exists only below 3 °K and only enters the superfluid state below about 0.002 °K, a temperature regime which only a few laboratories can achieve.

Upon cooling, all matter undergoes changes of state (phase transitions); the gas–liquid (liquification) and liquid–solid (freezing) are the best known examples. There is, however, another class of phase transition, the so-called second-order phase transitions, in which there is simultaneously both a loss in symmetry and the appearance of a new kind of order. Ferromagnetism (or magnetism for short) is such a case: the magnetic moments of the individual electrons align, thus constituting a new degree of order. This alignment stakes out a direction in space (albeit, arbitrarily) and so represents a condition of less symmetry than the higher-temperature isotropic state in which the magnetic moments are oriented randomly. A lesser known phenomena also accompanies the transition: new excitations called collective waves (or modes) appear, the name stemming from the fact that a large number of particles move collectively to produce a wavelike motion. For the ferromagnetic case, the collective mode is a wavelike precession of the magnetization around its equilibrium direction.

The lost symmetry and the accompanying collective modes of a superfluid are somewhat more subtle in character. The understanding grew out of the theory of superconductivity, first formulated by Bardeen, Cooper, and Schreiffer (BCS), and later refined by others. Ordinarily, the properties of matter are independent of the phase of the associated quantum mechanical wave function; this is not true in a superfluid, where the lost symmetry is called "broken gauge invariance." Broken gauge symmetry is also a subject of major concern to particle physicists.

In the BCS theory, electrons pair to form a kind of molecule, known as a Cooper pair. In ^{3}He, the spin angular momenta of the individual ^{3}He atoms add (rather than cancel, as in the case of electrons) while they simultaneously rotate about each other to produce a net orbital angular momentum. The collective modes involve various vibrations of the phase and the spin and orbital angular momentum of the pairs. Interestingly enough, the spectroscopy of the collective modes bears a close resemblance to that of atoms and free particles.[2] One can even classify the modes by their total angular momentum (called J) as in an atom. Rather than exciting the "atoms" with light, however, we use high-frequency sound waves.

In the past few years, the nature of the collective modes of ^{3}He has been largely uncovered, using ultrasonics, by workers at Northwestern,[3] Cornell,[4] and Saclay.[5] The frequencies of most of the collective modes can be varied by changing the temperature: when the frequency matches that of the sound, a very sharp and strong resonance structure is observed. A rather spectacular effect is observed on the application of a magnetic field[5]: the mode frequencies split linearly into multiplets, analogous to the Zeeman effect of atomic spectroscopy (the number of frequencies being given by $2J + 1$, from quantum mechanics). Large fields cause a nonlinear evolution of the modes which, in the atomic analogy, is termed the Paschen–Back effect.[6] The atomic analogy is limited to the long wavelength behavior of the collective modes. If the mode frequencies are examined at shorter wavelengths, they are found to depend on wavelength.[1,7]

What is perhaps most unusual is that the closed atomic shell atoms of the rare gas ^{3}He, which interact with each other via an isotropic interatomic potential, can condense into an anisotropic state complete with macroscopic orbital and spin angular momenta and with a rich collective mode spectra, the properties of which have much in common with excited atoms and free particles.

J. B. Ketterson, Northwestern University

1. N. David Mermin and D. Lee, Sci. Am. **235**, 56 (December 1976).
2. For a review, see P. Wolfle, Prog. Low Temp. Phys. **7a**, 191 (1981).
3. D. B. Mast, B. K. Sarma, J. R. Owers Bradley, I. D. Calder, J. B. Ketterson, and W. P. Halperin, Phys. Rev. Lett. **45**, 266 (1980); I. D. Calder, D. B. Mast, B. K. Sarma, J. R. Owers Bradley, J. B. Ketterson, and W. P. Halperin, *ibid.* **45**, 1866 (1980).
4. R. W. Gianetta, A. Ahonen, E. Polturak, J. Saunders, E. Zaise, R. C. Richardson, and D. M. Lee, Phys. Rev. Lett. **45**, 262 (1980).
5. O. Avenel, E. Varoquaux, and H. Ebisawa, Phys. Rev. Lett. **45**, 1952 (1980).
6. B. S. Shiraram, M. W. Meisel, B. K. Sarma, D. B. Mast, W. P. Halperin, and J. B. Ketterson, Phys. Rev. Lett. **50**, 1070 (1983); N. Schopohl, W. Warnke, and L. Tewordt, Phys. Rev. Lett. **50**, 1066 (1983).
7. B. S. Shivaram, M. W. Meisel, B. K. Sarma, D. B. Mast, W. P. Halperin, and J. B. Ketterson, Phys. Rev. Lett. **49**, 1646 (1982).

Superconducting Transistors

For several years researchers at a number of industrial laboratories, most notably IBM, have been investigating the use of Josephson junctions as switching elements in digital circuits.[1] A Josephson junction consists of two strips of superconducting metal separated by a thin insulating layer. Under the right circumstances, Cooper pairs (pairs of electrons bound weakly to each other inside the superconducting crystal) or quasiparticles (individual electrons) can flow from one strip to the other by "tunneling" through the insulator. Tunneling, a quantum effect with no classical analog, is the wavelike propagation of a particle (or in this case, a pair of particles bound together) through an otherwise forbidden region.

When a voltage is applied across the insulator there is a net tunneling current of quasiparticles from one electrode to the other. In addition, at zero voltage there is also present a dc Josephson current owing to the tunneling of paired electrons. The two conduction mechanisms result in a junction characteristic that is bistable, there being a Josephson state with zero resistance and a quasiparticle conduction state with relatively high resistance. Computer circuits using the controlled switching between these states have been designed and fabricated. Switching is induced either by magnetic fields applied to the junction or by controlling the magnitude and sequence in which currents are applied to the junctions.

The attractiveness of the Josephson junction as a switching element stems from its low switching energy, only a few μW, and its high switching speed, a few picoseconds. In future computer circuits, the low switching energy will be as important as the high switching speed. To avoid signal transit time limitations, the millions of devices contained in the computer must be crammed into a volume only a few centimeters on a side and the heat generated by the devices must be removed. Superconductivity offers an additional advantage in such systems since superconducting transmission lines can be made very small while retaining very wide bandwidth characteristics.

There are, however, considerable practical difficulties to the development of Josephson technology. The Josephson junction is very different from the transistors that make up all practical computer circuits, in that it has only two terminals, making it difficult to isolate the input from the output. Superconducting transformers can be used, but these take up considerable area. In addition, the bistable nature of the device necessitates threshold logic that places considerable demands on the tolerances of manufactured devices. Whether or not these practical problems can be solved is an open question.

A more transistor-like device that operates at superconducting energy levels could alleviate these problems and yet take advantage of the low energy of superconducting devices and the bandwidth of the superconducting lines. In 1978, Ken Gray at Argonne noted that nonequilibrium superconductivity and, in particular, a stacked junction structure consisting of three superconducting layers with two intervening tunnel junctions, offered the possibility of a transistor-like device.[2] By using one junction to inject quasiparticles into the middle superconducting film, Gray showed that it was possible to create an excess quasiparticle density in the thin middle film of such a magnitude that the current extracted from the other junction actually exceeded the current that created the excess density. Although there was a current gain, the injection current was at a higher voltage than the extraction voltage, so there was a voltage loss. Gray's experiments used aluminum as the superconductor because it offered ease of fabrication and a convenient time scale (100 nsec) for experimentally investigating nonequilibrium phenomena. Gray pointed out that other superconducting materials would offer much faster responses for device applications.[3]

At IBM, Raider and Drake had developed techniques for making rugged, high-quality, high-current-density junctions for Josephson applications with niobium as one of the electrodes.[4] Using these techniques, Faris, Raider, Gallagher, and Drake fabricated a niobium/oxide/thin niobium/oxide/lead alloy double sandwich structure that they called the quiteron.[5] The quiteron's transistor-like properties arise when electrical energy is injected into the middle superconducting layer, exciting it into a nonequilibrium state, a condition in which some of the Cooper pairs are broken apart into individual electrons (referred to in this case as quasiparticles). The uneasy mixing of the quasiparticle and Cooper-pair populations drastically alters the current–voltage behavior of the junction, giving it the abrupt turn-on quality of an electrical switch.

High-speed measurements showed evidence for some fast (110 psec) response, but also a substantial slow (10 nsec) response.[6] The slow response reflected a heat removal bottleneck caused by the inability of phonons created as a result of the decay of the nonequilibrium quasiparticle distribution to escape easily from the entire structure.

A device structure that may avoid the phonon removal bottleneck present in the stacked junction devices is being investigated by Hunt and Buhrman.[7] Their structure consists of two edge junctions formed by a narrow superconducting line stepping over two superconducting films separated from each other by a thick insulator. Removal of the energy resident in the nonequilibrium quasiparticle distribution should be by direct quasiparticle diffusion, rather than by the slower quasiparticle recombination and phonon escape.

Even if significant gain at high speed can be demonstrated, the question of whether these schemes will result in a practical cryogenic transistor is not clear. Practical questions remain about the degree of isolation of the control electrode from the output, the relationship between the impedances of the input and output, and the manufacturability of the experimental structures.[8]

W. J. Gallagher and G. Present, IBM

1. J. Matisoo, Sci. Am. **242**, 50 (May 1980).
2. K. E. Gray, Appl. Phys. Lett. **32**, 392 (1978).
3. K. E. Gray, in *Nonequilibrium Superconductivity, Phonons, and Kapitza Boundaries*, edited by K. Gray (Plenum, New York, 1980), pp. 149–150.
4. S. I. Raider and R. E. Drake, IEEE Trans. Magn. **MAG-17**, 229 (1981).
5. S. M. Faris, S. I. Raider, W. J. Gallagher, and R. E. Drake, IEEE Trans. Magn. **19**, 1293 (1983).
6. W. J. Gallagher, S. M. Faris, S. I. Raider, and R. E. Drake, Paper GN-18 presented at the meeting of The American Physical Society, Los Angeles, March, 1983.
7. B. D. Hunt and R. A. Buhrman, IEEE Trans. Magn. **MAG-19**, 1155 (1983).
8. Phys. Today **36**, 19 (May 1983).

Nanosecond Resolution Time-Resolved X-Ray Diffraction

Nanosecond resolution time-resolved x-ray diffraction investigations[1] of the structure of silicon during pulsed laser annealing have been made utilizing a synchrotron x-ray source. These experiments represent a thousandfold increase in time resolution over that obtained using conventional laboratory x-ray sources. The results of these experiments provide unique information on the laser annealing process[2] in silicon (*Physics News in 1982*, p. 43), and demonstrate the possibility of using synchrotron sources to investigate a variety of transient structural phenomena on a nanosecond (billionth of a second) time scale.

The measurements were performed at the Cornell High Energy Synchrotron Source (CHESS), making use of the pulsed time structure that is inherent to synchrotron radiation sources. By synchronizing the firing of 15 nsec laser pulses from a ruby laser with the 0.15 nsec x-ray pulses from CHESS, scientists from Oak Ridge National Laboratory and CHESS were able to probe the lattice structure (thermal strain) of silicon both during and after pulsed laser irradiation using time-resolved x-ray Bragg reflection profile measurements. Analysis of the angular distribution of the x-ray scattering yielded thermal strain distributions from which time-resolved lattice temperature distributions were determined, providing the first measurements[1] of the temperatures and temperature gradients in silicon during pulsed-laser annealing.

These results showed directly that pulsed-laser annealing in silicon involves thermal melting of a thin (< 1 μm) surface layer followed by rapid epitaxial recrystallization as a result of heat flow into the bulk; these measurements were in agreement with optical studies[3] and electrical conductivity[4] measurements. The x-ray results further showed that to within an uncertainty of 50–75 °C, the liquid–solid interface temperature was at the melting point (1410 °C) of silicon throughout the molten phase of the annealing process. Thermal gradients below the interface were 2000 °C/μm during the melting phase and 1000 °C/μm during the regrowth phase of the annealing process. Detailed information of this nature is needed for testing models of heat flow and crystal growth under highly nonequilibrium conditions.

These results demonstrate the enormous potential of synchrotron sources for real-time investigations of phase transformations and transient structural phenomena occurring on nanosecond time scales and suggest that even subnanosecond resolution measurements would be possible through the use of specialized techniques.

F. W. Young, Jr., Oak Ridge National Laboratory

1. B. C. Larson, C. W. White, T. S. Noggle, and D. M. Mills, Appl. Phys. Lett. **42**, 282 (1983); B. C. Larson, C. W. White, T. S. Noggle, J. F. Barhorst, and D. M. Mills, Phys. Rev. Lett. **48**, 337 (1982).
2. J. M. Poate and W. L. Brown, Phys. Today **35**, 24 (June 1982).

3. D. H. Lowndes, G. E. Jellison, and R. F. Wood, Phys. Rev. B **26**, 6747 (1982).
4. G. J. Galvin, M. O. Thompson, J. W. Mayer, R. B. Hammond, N. Paulter, and P. S. Peercy, Phys. Rev. Lett. **48**, 33 (1982).

Diluted Magnetic Semiconductors

The physics of semiconductors is a highly sophisticated science which has had a profound impact on all aspects of our technological civilization. For example, the development of the semiconductor "chip" has completely revolutionized the fields of computers and communications, and is gradually beginning to touch most facets of everyday life.

There are elemental semiconductors (e.g., silicon) and compound semiconductors (gallium arsenide). It is also possible to form multicomponent semiconductor alloys (such as the ternary alloy GaAlAs) whose properties can be continuously varied by controlling the composition.

Recently, particularly in the last six years of so, a new group of semiconductor alloys known as diluted magnetic (or "semimagnetic") semiconductors[1] has attracted a great deal of attention worldwide. Diluted magnetic semiconductors (DMS) are alloy materials whose crystal lattice contains substitutional magnetic ions. CdMnTe is an example of such a system: a fraction of the Cd atoms in the "host" CdTe crystal are replaced at random by a magnetic ion (in this example, manganese). Many such ternary systems can be prepared.[2]

These materials are interesting and important for three reasons. First, as in the case of nonmagnetic ternary alloys, the properties of DMS—their energy gap, lattice parameter, and so forth—can be carefully tailored. One striking example is the opaque semiconductor CdTe, which gradually becomes transparent to the eye as more and more Cd atoms are replaced by Mn.[3]

Second, owing to the fact that DMS are diluted, and therefore disordered, magnetic alloys, these materials display extremely interesting magnetic properties. For example, at cryogenic temperatures, DMS become "spin glasses," that is, the spins associated with the magnetic ions "freeze" in a formation which has no long-range order.[4] Furthermore, in the case of DMS, the mechanism responsible for such random freezing, referred to as *lattice frustration*, is rare in nature, making DMS of particular interest to the student of magnetism.

Third, the presence of the magnetic ions in the DMS lattice leads to a strong interaction—the so-called *exchange interaction*—between the spins of the localized magnetic moments and those of the band electrons, the electrons responsible for the properties specific to semiconductors. This in turn has a profound effect on many optical and electrical properties, completely unique to DMS.[5] An example of such an exchange-induced optical effect is the observation in CdMnTe of gigantic Faraday rotation (the rotation of the plane of polarization of transmitted light when a magnetic field is applied), typically exceeding by two orders of magnitude the Faraday rotation observed in nonmagnetic semiconductors, such as CdTe.[6] An example of an electrical phenomenon related to exchange interaction is the observation of a dramatic negative magnetoresistance in HgMnTe. The conductivity at very low temperatures has been observed to increase by *seven orders of magnitude* in a field of 70 kG.[7]

The exchange-related phenomena in DMS, such as those illustrated above, are in effect "cross products" of two sophisticated disciplines, semiconductor physics and magnetism, which seldom overlap. This circumstance, and the novelty of the phenomena, makes them of interest to basic research. Also, the mere size of the effects such as those described above offers the prospect of eventual exploitation in semiconductor devices.

Until recently, most of the activity in this area has been concentrated in four institutions: Purdue University, which has pioneered DMS research in the U. S. and has been continuously active in this field since 1969; the Warsaw-based Polish semiconductor group, which has been largely responsible for propagating DMS research in the European physics community since about 1973; Ecole Normale Superieure in Paris; and Instituto Venezolano de Investigaciones Cientificas (IVIC) in Venezuela. Recently, however, activity in DMS research has been spreading extremely rapidly around the world. While in the two-year period 1972–73 there were only four publications on the subject, and 20 in 1977–78, there were over 90 articles on DMS in 1981–82 in major refereed journals. In diluted magnetic semiconductors, important electrical, magnetic, and optical phenomena are all manifested in a single substance, a unique situation from which fascinating new physics may emerge in the next several years.

J. K. Furdyna, Purdue University

1. J. K. Furdyna, J. Appl. Phys. **53**, 7637 (1982).
2. A. Pajączkowska, Prog. Crystal. Growth Charact. **1**, 289 (1978).
3. N. Bottka, J. Stankiewicz, and W. Giriat, J. Appl. Phys. **52**, 4189 (1981).
4. R. R. Galazka, S. Nagata, and P. H. Keesom, Phys. Rev. B **22**, 3344 (1980).
5. J. Mycielski, *Recent Developments in Condensed Matter Physics*, edited by J. T. Devreese (Plenum, New York, 1981), Vol. 1, p. 725.
6. J. A. Gaj, R. R. Galazka, and M. Nawrocki, Solid State Commun. **25**, 193 (1978).
7. T. Wojtowicz and A. Mycielski, Physica B **117** and **118**, 476 (1983).

Tunable Infrared Color Center Lasers

Wavelength-tunable near-infrared lasers based on color centers in alkali halide crystals have been developed recently and are gaining increasing importance in research areas such as molecular spectroscopy and fiber optics. These lasers are similar in their design to the widely used tunable laser systems based on various dyes in organic solvents. In principle, the only difference is the active material, which is a cryogenically cooled crystal slab instead of a flowing dye solution. The importance of these new solid-state lasers is their potential for broadly tunable laser operation in the near-infrared range, where dye lasers fail to operate.

The active material of color center lasers are ionic crystals containing particular point defects ("color centers") in which an electron takes the place of a dislodged ion.[1] This electron has associated with it energy states that do not ordinarily occur in the crystal. Owing to the strong coupling of the electron to lattice vibrations the optical transitions between these levels give rise to broad spectral bands with a sizeable frequency shift between absorption and emission bands. Typical color center absorptions lie in the visible range (giving color to a normally transparent crystal), with broad emission bands in the near-infrared (1–3 μm) range. Pumping of the absorption transition with appropriate laser sources, such as argon or krypton lasers, can produce infrared laser light tunable over most of the spectral width of their emission band, typically about 15% of the central frequency.

All laser-active color centers developed so far are complex defects employing the association of simple *F* centers (color centers in which electrons are trapped by a negative ion vacancy) with other point defects. The first group developed,[2–4] based on *F* center association with Li^+ or Na^+ defects, provides stable tunable laser operation in the 2.2–3.3 μm range and is available in commercial form. Extensive efforts to develop another class of complex defects (F_2^+ centers) with broad emissions in the 0.8–2.0 μm range led to various successful laser operations in the laboratory.[5,6] There is promise for an extended range of tunable laser operation up to 4 μm.[7]

Recently a new laser active defect type has been discovered in various Tl^+-doped alkali halide crystals, consisting of an electron bound to a Tl^+ ion–anion vacancy complex.[8] These defects could be produced in high concentrations in a number of host lattices. Stable and broadly tunable laser operation has been obtained, so far, with KCl and KBr crystals. The laser wavelength could be continuously tuned over the 1.4–1.7 μm range using a Nd^{3+}:YAG laser (operating at 1.06 μm) as a pump source. The new materials are highly stable and have a 20% conversion efficiency. The KCl system has recently been operated in a mode-locked condition using synchronous pumping.[9] Owing to the long fluorescence decay time of the color center, a novel regime for mode locking was observed; in contrast to dye lasers, extremely narrow pulses (100 psec width) were obtained with pumping far above lasing threshold.

The new laser systems reported here are expected to find widespread use in fiber optics research, where light propagation behavior can now be conveniently studied in a wavelength region of low fiber loss and minimum dispersion.

Fritz Lüty, University of Utah

1. K. Nassau, Sci. Am. **243**, 124 (October 1980).
2. B. Fritz and E. Menke, Sol. State Commun. **3**, 61 (1965).
3. L. F. Mollenauer and D. H. Ohlsen, Appl. Phys. Lett. **24**, 386 (1974).
4. R. Beigang, G. Litfin, and H. Welling, Opt. Commun. **22**, 269 (1977).
5. L. F. Mollenauer, Opt. Lett. **1**, 164 (1977).
6. W. Gellermann, F. Luty, K. P. Koch, and H. Welling, Opt. Commun. **5**, 430 (1980).
7. I. Schneider, Opt. Lett. **7**, 271 (1982).
8. W. Gellerman, F. Luty, and C. R. Pollock, Opt. Commun. **39**, 391 (1981).
9. L. F. Mollenauer, N. D. Viera, and L. Szeto, Opt. Lett. **7**, 9 (1982).

A New Class of High-Performance Permanent Magnets

Scientists at the General Motors Research Laboratories have discovered a neodymium–iron–boron (Nd–Fe–B) alloy suitable for producing high-strength permanent magnets.[1] It is expected that this discovery will revolutionize the entire electric motor business.

Such high-strength permanent magnetic materials may profoundly effect costs and permit production of smaller and lighter electrical devices such as motors, speakers, and meters. Currently, the premier material is a compound containing samarium (Sm) and cobalt (Co). Sm is a rare element while Co is a relatively expensive transition metal. Materials scientists have long desired to formulate a high-strength magnetic material from the so-called light rare earths, such as Nd or Pr (praseodymium), and the transition metal Fe–all of which are abundant and relatively inexpensive.

Previously, the barrier to producing the necessary high coercivity (resistance to demagnetization) in these alloys was the absence of suitable intermetallic phases. However, the General Motors scientists discovered a family of stable compounds that showed exceptional permanent magnet properties. High coercivity could not at first be achieved in these materials because the traditional approach was to grind the material to a particle size smaller than the optimum magnetic domain size. Domains are tiny regions that act as discrete magnets. If the grain size exceeds the domain size, a domain wall forms and this leads to low coercivity. For $Nd_2Fe_{14}B_1$ and $Pr_2Fe_{14}B_1$ compounds, the optimum grain size is much smaller (20–100 nm) than could be achieved by conventional grinding methods.

Instead the desired grain size was achieved by melt spinning. In this process a thin stream of molten alloy is directed onto the surface of a spinning metal wheel to produce a rapidly quenched ribbon.

The GM scientists are currently investigating the fundamental properties of this new class of materials. They suspect that further improvements in the magnetic strength of these surprising materials are likely.

John Croat, General Motors

1. J. J. Croat, J. F. Herbst, R. W. Lee, and F. E. Pinkerton, Appl. Phys. Lett. (to be published).

CRYSTALLOGRAPHY

Crystallography is the science which describes the geometrical structure and properties of crystals. A crystal is a three-dimensional periodic arrangement of atoms in solids. X-ray crystallography is the study of crystal structure using x rays which bombard the crystal and reveal its structure in the characteristic diffraction pattern which results.

Polyoma Virus

Recent x-ray crystallographic studies have provided important information about the structure and molecular biology of two important mammalian viruses: polyoma, an agent that can cause tumors in mice, and human influenza. Polyoma appears spherical in the electron microscope, but is known to have a coat or shell that is built up from many copies of a single protein molecule. The interior of the particle houses the viral DNA. X-ray images of polyoma have revealed a very surprising arrangement for the protein "tiles" comprising the virus coat.

In 1956 Crick and Watson argued that, since the genome of a virus is small, genetic economy demands that the coat of a virus be composed of many copies of only a small number (often one) of protein subunits.[1] They also suggested that all protein subunits should be in identical environments to simplify the observed spontaneous assembly of the virus. The largest coat is obtained when the protein subunits are arrayed on the surface of an icosahedron, with five subunits arranged around each of its 12 fivefold axes.

The prediction that spherical viruses should have 60 (12×5) copies of each subunit was confirmed for a number of cases, but counterexamples eventually emerged. In 1962 Caspar and Klug proposed an extension of the icosahedral model in which the 20 equilateral triangles forming the faces of the icosahedron are subdivided or faceted into 20 smaller triangles ($T=20$).[2] This subdivision allows protein subunits (with $T=60$) in the viral coat, although the subunits occupy not identical but only quasiequivalent environments. The number of contacts a subunit must make is still severely restricted. In the case $T=3$, for example, six small triangles meet at the center of each icosahedral face, creating a local sixfold axis which can become the center for a hexamer of protein subunits. This $T=3$ particle thus contains 180 subunits: 12 pentamers located at the strict fivefold axes of the icosahedron, and 20 hexamers at the centers of the faces. The clustering of subunits into hexamers and pentamers can take place for all values of T greater than 1, and the subunits must be flexible enough to accommodate this. Viruses having $T=3$ arrangements of subunits have been observed, and until recently it was generally accepted that all spherical viruses were built according to the Caspar and Klug model.

Later work showed that the protein coat of polyoma virus consists entirely of pentamers, although it had been categorized as a $T=7$ particle containing both hexamers and pentamers.[3] Their conclusion is based upon an image of the entire virus formed at 22.5-Å resolution by single-crystal x-ray diffraction analysis. The image shows clear fivefold symmetry of all the subunit aggregates in the virus coat. Thus, there exist pentamers with six nearest neighbors—termed hexavalent pentamers by the authors. This awkward arrangement means that subunits must make a large number of different contacts of nearly equivalent energy, and the asymmetrical environment of many of the pentamers makes it difficult to understand the accurate, spontaneous assembly of the virus.

The image of polyoma virus was processed using a novel algorithm that enforced two constraints: flat electron density in the solvent region surrounding the particle and fivefold symmetry for the entire icosahedron (*not* for the unexpected pentamers individually). The results have recently been confirmed by electron microscopic analysis of polyoma mutants that form tubes instead of spherical coats.[4] The tubes also appear to be composed exclusively of pentamers.

It is well known that, theoretically, it is impossible to tile the plane with regular pentagons. In general, the same is true for the sphere. In practice, as shown by polyoma, one can use any shape tile if the gaps are filled with grout. The nature of the grout in polyoma remains to be determined.

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1. F. H. C. Crick and J. D. Watson, Nature **177**, 473 (1956).
2. D. L. D. Caspar and A. Klug, Cold Spring Harbor Symp. Quant. Biol. **27**, 1 (1962).
3. I. Rayment, T. S. Baker, D. L. D. Caspar, and W. T. Murakami, Nature **295**, 110 (1982).
4. T. S. Baker, D. L. D. Caspar, and W. T. Murakami, Nature **303**, 446 (1982).

Influenza Virus

Influenza virus is a larger and more complex agent than polyoma. Its outermost layer is a membrane coat pinched off from the host cell surface during maturation. This viral membrane contains two glycoproteins, a neuraminidase (NA) and a hemagglutinin (HA) that define most interactions of the virus with cells or molecules.

The structure of both of these molecules has now been determined by x-ray diffraction analysis.[1,2] They represent two of the first membrane-bound proteins to be successfully crystallized and studied in this way. NA catalyzes the removal of a terminal sugar residue from center polysaccharides and, thereby, probably facilitates the mobility of the virus to and from the site of infection. HA, in contrast, has no known catalytic activity, but rather serves to bind the virus to host cells.

Both of these molecules are anchored in the membrane through strongly hydrophobic regions that were cleaved during the solubilization process required for crystallization. The soluble portions of the molecules, which extend out from the viral membrane *in vivo*, display complex and almost bizarre architecture by the standards of the usual globular protein. HA is a trimer comprising a stalk-like region extending some 76 Å from the membrane and crowned by a globular region containing the sites that bind to specific molecules on cell surfaces and loci that stimulate the host immune response. The stalk is a triple-stranded coiled coil of alpha-helices unique among globular proteins.

NA is tetrameric and also has a flower-like aspect, consisting of a fourfold symmetric, propeller-shaped head attached to the viral membrane by a slender stalk that was removed prior to crystallization. The catalytic site of NA has been located by synthesizing images with and without the reaction product sialic acid bound. In addition, many of the antigenic sites in NA and HA have been located. Changes in the amino acid sequence of these proteins in different strains of influenza virus alter the antigenic specificity of the virus, and allow it to escape the immune response directed against previous strains. Thus, we can be reinfected with influenza every few years as new viral strains emerge. These changes have been localized exactly on the protein molecules.

Although no simple strategy for disease control is obvious from these observations, important experiments involving viral peptides that define potential antigenic determinants common to all virus strains have become possible.[3]

These, in turn, may lead to much more broad-spectrum vaccines. All this results from the exact description of the viral surface that makes it possible to understand in atomic detail the interaction of influenza virus with its surroundings.

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1. J. N. Varghese, W. G. Laver, and P. M. Colman, Nature **303**, 35 (1983).
2. I. A. Wilson, J. J. Skehel, and D. C. Wiley, Nature **289**, 366 (1981).
3. Richard Lerner, Sci. Am. **248**, 66 (February 1983).

Basic New Techniques in Crystallography

The first crystal structure analyses were done by W. L. Bragg almost 70 years ago, and the application of his technique, diffracting x rays from crystals, shows no signs of slowing down. The size of atomic assemblies that can be imaged by the technique has gradually grown from 1 or 2 atoms in 1913 to 10^6 atoms, in some cases, today. Developments now in the research stage may in time push the technique still further. We will briefly consider four of these.

Crystallographic structure analysis proceeds first by measuring the diffraction pattern of a crystal specimen produced by x rays or neutrons, then by associating the correct phase for each point of the diffraction pattern, and finally by Fourier inverting the correctly phased pattern to produce an image of the specimen. The second step, that of phasing, is generally the hard one. The amplitude of the diffracted x-ray radiation is a complex number. While it has always been easy to measure x-ray intensity (given the square of the amplitude), measuring the phase of the amplitude is difficult.

Over the years a number of methods for phasing have been developed, but it has generally been assumed that the task of simultaneously measuring both the phase *and* the intensity at each point in the pattern could not be done. Now, however, something closely resembling this has been done, at least in simple cases, by Benjamin Post of the Polytechnic Institute of New York and some of his colleagues.[1]

Post's method consists in setting the crystal in such an orientation that x rays are diffracted into two Bragg reflections simultaneously, and then observing the behavior of the two diffraction intensities as the crystal orientation is varied slightly about this setting. In 1977 Post pointed out that the dynamical theory of crystal diffraction, first developed by Paul Ewald in 1917, predicts that the detailed behavior of the diffraction intensities in this situation depends on the sum of the phases at three points in the diffraction pattern, namely the two diffraction pattern, namely the two diffraction points and the point which is the negative of their vector sum. The sum of the phases for such a triplet of points is an important quantity in the phasing process, and is called a three-phase structure invariant. Post's observation, therefore, amounted to the suggestion that the three-phase structure invariants can be measured by observing the behavior of the diffraction intensities in the neighborhood of the positions in which the crystal is doubly diffracting. This suggestion has since been experimentally demonstrated on a number of rather simple crystals.[2]

For many years crystallographers have been using mathematical techniques to *estimate* the three-phase structure invariants from the diffraction intensities, and deducing phases from these estimates. The technique as a whole is called the direct phasing method, and is an extremely convenient technique for phasing, requiring as it does nothing more than the measured diffraction intensities. Both steps, the estimation of the invariants and the deducing of the phases, present difficulties, but the method usually succeeds for assemblies of up to about 100 atoms. What Post's technique promises to do is to allow the invariants to be *measured*, at the cost only of a more detailed exploration of the diffraction intensities in the regions where double diffraction is taking place.

A second development is due to Gerard Bricogne of the College of Physicians and Surgeons at Columbia.[3] His work is aimed at improving both steps in the direct phasing method, with the intention of allowing the method to succeed with structures much larger than 100 atoms. Bricogne's methods are highly mathematical and will not be explained here, but preliminary tests now taking place at several centers, using diffraction data from structures much larger than could previously have been attempted by direct phasing, are encouraging.

The third development can be ascribed to the group headed by Herbert Hauptman, centered at the Medical Foundation of Buffalo.[4] For years the structures involving really large assemblies of atoms have been solved by a phasing technique based on the comparison of two or more diffraction patterns obtained by varying the number and position of atoms not properly belonging to the structure, but intentionally added to produce small changes in the diffraction intensities; when properly interpreted these changes can be used to determine the diffraction phases of the original structure. (In a related technique, the changes are induced not by adding atoms but by exciting resonances in specific atoms by tuning the x rays close to the appropriate atomic absorption edges.) Hauptman, who was one of the developers of the direct phasing methods, has now generalized the concept of structure invariant to apply to the case of several diffraction patterns, and has developed methods of estimating the invariants in this case. The result could be a major improvement in the strength and convenience of the phasing techniques for very large structures.

The previous developments all considered the problem of phasing the diffraction patterns of crystals of increasingly complex atomic assemblies. The last development, however, assumes that at a certain level of complexity crystallization of the assemblies may not be feasible. An example is the giant assembly known as a single biological cell, which nature does not make to a pattern sufficiently precise to permit a crystal formed of such cells to exist. With this in mind, a team composed of D. Sayre and R. P. Haelbich at IBM Research, and J. Kirz and W. B. Yun at the State University of New York at Stony Brook, has embarked on an attempt to see whether diffraction patterns from single giant assemblies can be obtained.[5] Calculations suggest that by using x rays of wavelength roughly 30 Å, the diffraction patterns from such minute specimens, although still extremely weak, should be measurable at intense synchrotron x-ray sources. Current sources are still marginal for this purpose, and no pattern has as yet definitely been observed, but an improved source due to be installed at the Brookhaven Synchrotron Radiation Source in 1984 should be able to provide observable patterns. Should this be true, the way may be open for the first time for the three-dimensional imaging of such assemblies at 15-Å resolution.

David Sayre, IBM

1. B. Post, Phys. Rev. Lett. **39**, 12 (1977); Acta. Crystallogr. Sect. A **35**, 17 (1979).
2. Phys. Today **35**, 17 (November 1982).
3. G. Bricogne, Acta Crystallogr. (in press).
4. H. Hauptman, Acta Crystallogr. Sec. A **38**, 632 (1982).
5. D. Sayre, R. P. Haelbich, J. Kirz, and W. B. Yun, in *Proceeding of the Conference on X-Ray Crystallography, 14–16 September 1983*, edited by G. Schmal (Gottingen, Springer, in press).

EDUCATION IN PHYSICS

Physics educators will mark 1983 as the year in which the rapidly deteriorating state of science education broke through to public attention. The problems inherent to what is now called the "crisis in physics education" can be grouped under the two broad headings of "The Physics Teacher Shortage" and "The Decline in the Quality and Quantity of Physics Instruction," subjects examined in the following article.

Although these problems had been a matter of great concern to scientists and their professional societies for a number of years, there was little public awareness of the problem. The apparent lack of interest was epitomized by the dismantling (in 1982) of the Science Education Directorate at the National Science Foundation, an agency that had come to symbolize the national interest in and commitment to science education ever since NSF support enabled Jerrold Zacharias of MIT to form the Physical Science Study Committee in 1956.

In a remarkable turnabout, science education has become one of the hottest topics in Washington during 1983, as a myriad of proposals surfaced to address the newly discovered crisis. In the House of Representatives two bills sponsored by Congressmen Don Fuqua and Carl Perkins were combined into HB 1310 and passed following an outpouring of support from scientists, industry, and the military. This bill provides $425 million in support for science education. The Senate versions had not yet passed as of this writing. One note of discord surfacing during the hearings was a dispute over whether the National Science Foundation or the Department of Education should have primary responsibility for science education. In the end this was resolved by giving the NSF $130 million and the Department of Education $295 million.

Although the final characteristics of the federal involvement in science education for 1984 are not yet determined, it is safe to say that there is now general recognition that the federal government does have a responsibility in this area and that 1983 will mark the year in which this interest was reconfirmed.

Learning about physics is, of course, not restricted to the classroom. Nor is education in physics restricted to those who intend to become scientists. Information about physics comes to the public at large in a variety of ways: at museums, on television, and on radio. Articles below take up these subjects.

Readers are served by a wide spectrum of newspapers and magazines, extending from the semitechnical monthlies such as *Physics Today, Astronomy,* and *Scientific American* to the more popular journals such as *Discover, Science 83, Omni, Science Digest,* and *Popular Science*. One can get the latest-breaking physics news in such weekly magazines as *Science, Science News, New Scientist,* and *Nature*.

Jack Wilson, American Association of Physics Teachers

The Crisis in Physics Education

The shortage of qualified science teachers is particularly acute in mathematics and physics and only slightly less so in chemistry. Biology teachers on the other hand seem to be in relatively good supply and often find themselves pressed into service in other areas. The enormous declines in physics enrollments at the secondary level actually tends to mask the shortage, but statistics gathered by the American Institute of Physics, the National Science Teachers Association (NSTA), and the American Association of Physics Teachers (AAPT) put the situation in stark relief.

From 1971 to the present there has been a decline of 65% in the number of secondary science teachers being trained. In 1981, 42 of 45 states reporting cited a shortage in physics teachers. Only 2% of recent physics bachelors selected teaching as a profession. An estimate prepared by AAPT and NSTA indicates that at least 30% of those presently teaching physics are underqualified.[1]

The physics teacher shortage is complicated by the long-term decline in physics enrollments and the enormous regional variation in conditions. In the Northeast and Midwest declining school enrollments, bleak industrial opportunities, and strong union rules on seniority combine to lessen the severity of the shortage, as there is little incentive for science teachers to enter industry.

In the West, Southwest, and South, however, great economic growth and a burgeoning population have created a demand for science teachers while at the same time siphoning off the best science students into industrial positons.

While the lack of physics teachers presents the physics community with an immediate problem, the long-term decline in the quantity and quality of physics courses taken in the secondary schools presents perhaps the more difficult problem. Physics enrollments represent only 3.1% of the total secondary science enrollment.[2] In 1895 95% of all graduates took physics![3] For women the picture is worse, inasmuch as female high school students are only half as likely as males to have taken physics. The decline is also independent of level: the number of U.S.-born physics graduate students has declined from 2900 to 1700 in the period 1970 to 1981, and the number of physics doctoral degrees as a percentage of all sciences has declined from 11% to 7.3% during the same period. Clearly scientific literacy, particularly in physics, is increasingly restricted to a small percentage of the population, a trend that has dangerous implications for access to technical careers.

The science and mathematics literacy of the general student population has apparently continued to decline. The Educational Testing Service has reported that the scores on the quantitative portion of the Scholastic Aptitude Test (SAT) have declined by 22 points in the period 1970–81. Only one third of the nation's 17,000 school districts require more than one year of mathematics and science for graduation.[1] An NSF survey revealed that only 7% of adults were deemed scientifically literate.[4]

When the science and mathematics literacy in the U.S. is compared to that in other countries, American students are at or very near the mean at ages 10 and 14 but fall to almost one standard deviation below the mean by age 18.[5] Such statistics are complicated by the effects of American mass education being compared to more elite forms found in other countries. Interestingly, Japanese students perform significantly above the mean at all ages for which statistics are available. The Japanese school year is also longer (240 days) than the U. S. (180 days) and the day is longer as well.[6] The U.S. fares no better in comparison with other industrialized countries. Izaak Wirszup of the University of Chicago was one of many responsible for arousing public opinion when he presented powerful congressional testimony concerning the differences in the commitment to science and mathematics education between the USSR and U.S.[7]

Just as the NSF Science Directorate was being abolished, the National Science Board Commission on Pre-College Education in Mathematics, Science, and Technology was created. The commission's first report, "Today's Problems—Tomorrow's Crisis," was issued in the fall of 1982.[8] Curiously, one of its conclusions read as follows: "Apparently, no consensus has been reached that the future prosperity and international position of the United States depends critically upon broader public attainment in mathematics, science, and technology." This assessment was to be refuted in 1983 as education, industry, the military, and interested citizens rallied to the support of improved and increased science education.

This was precisely the activity called for earlier by Senator John Glenn before the National Convocation on Pre-College Education in Mathematics and Science sponsored jointly by the National Academy of Sciences and National Academy of Engineering.[9] The Education Commission of the States developed an agenda of activities for state and local officials in their report "Action for Excellence."[10]

The science societies were also active in the science education area during 1983. Most worked together with the American Association for the Advancement of Science (AAAS) as part of the Coalition for Education in the Sciences.[11] The American Association of Physics Teachers, the National Association of Biology Teachers, The National Association of Geology Teachers, The American Chemical Society Education Division, and the National Science Teachers Association formed the Council of Science Teaching Associations to discuss common problems and propose solutions.

The AAPT "Crisis Committee" developed a list of actions to be taken toward a solution and initiated the development of a "Resource Kit for Underprepared Physics Teachers." The American Physical Society (APS) Education Committee and AAPT formed the joint "College High School Interaction Program" to pair high school teachers with college teachers.

Some of the reforms suggested include: higher pay for mathematics and science teachers (if not for all teachers), the use of the "Master Teacher" concept, scholarships for prospective teachers, retraining programs for underqualified teachers, new types of teacher-training programs, cooperation with industry, creation of endowed chairs of physics teaching, increased entrance standards for colleges and universities, increased high school graduation requirements, and so on.

The Department of Education appointed its own commission, The National Commission on Excellence in Education led by David P. Gardner, the new president of the University of California. Their report, "A Nation at Risk, The Imperative for Educational Reform," contained a vigorous criticism of the U. S. educational system and a strong call for reform.[12] Their dire assessment was epitomized by this provocative comparison: "If an unfriendly foreign power had attempted to impose on America the mediocre educational performance that exists today, we might well have viewed it as an act of war."

Jack Wilson, American Association of Physics Teachers

1. "Report of the Assembly of Society Officers," American Institute of Physics, March 1983.
2. Science and Engineering Education for the 1980's and Beyond,NSF 80–78, October (1980), p. 47.
3. J. Layman and T. Ingoldsby, Phys. Today **36**, 52 (September 1983).
4. Jon D. Miller, Daedalus **112**, 29 (1983).
5. L. C. Comber and J. P. Keeves, *Science Education in Nineteen Countries* (Wiley, New York, 1973), Vol. 159.
6. Educ. Week, **2–39**, 57 (1983).
7. I. Wirszup, Educ. Leadershp **38**, 358 (1981).
8. "Today's Problems, Tomorrow's Crisis," A Report of the National Science Board's Commission on Pre-College Education in Mathematics, Science, and Technology (Fall, 1982).
9. "Science and Mathematics in the Schools: Report of a Convocation" National Academy of Sciences and National Academy of Engineering (May 1982).
10. "Action for Excellence," A Report of the Education Commission of the United States, 1983.
11. "A Developing Crisis," American Association for the Advancement of Science (April 1982).
12. "A Nation at Risk, The Imperative for Educational Reform," A Report of the National Commission on Excellence in Education (Spring 1983).

Physics and Science on TV: 1983

Commercial TV. Only two years ago, in the wake of a dozen new science magazines in print, network programmers were eager to broadcast physics and science on prime-time TV. CBS's *UNIVERSE* and ABC's *OMNI* were two of their more ambitious new programs, featuring glossy reports and big-name hosts. Physics, chemistry, and biology were pitted head to head against the proven winners on the other networks—situation comedies, dramas, nightly magazines, and movies. But runaway science magazine subscriptions don't even cause ripples in the truly massive audience pool of network TV. The scientific nice guys finished last in the Nielsens. Today, no regular science shows, let alone shows on physics, air on network TV.

Perhaps more regrettable, and even alarming, is that no regular science programs for children appear. This lack comes as a bitter disappointment to those who believe TV can and should do more to reduce widespread scientific ignorance.

Most of the science that did appear on commercial networks this year was inadvertant and perhaps even distorting.[1] George Gerbner's detailed studies[2] reveal, for example, that six out of ten prime-time programs on commercial television involve "a theme or aspect of life explicitly and unambiguously related to science, technology, or engineering." The problem is that these themes and aspects are more often than not inaccurate or misleading and cast science in a negative light. Gerbner's data go on to show that as people watch more television, their confidence in the scientific community declines.

News on Commercial TV. All three networks do run some science reports, without any special emphasis on physics, as part of

Shooting report on a fuel-efficient flywheel car. At the wheel is Prof. Andrew Frank of the University of Wisconsin at Madison, the car's developer.

their evening and morning new shows. Science stories are usually associated with major ecological, health, and space issues. One of the biggest physics stories of the year, the discovery of the *W* particle at CERN, was nearly ignored by network news. Only *CBS MORNING NEWS* aired a relatively detailed report on the discovery and its meaning. Unlike, say, medical stories, physics is not seen by most news assignment editors as relating directly to people's lives. Physics is considered complicated and often difficult to televise.

Local commercial TV news, which in many areas commands greater audiences than does the network news, again prefers medical stories over hard science. Often local reporters are not experienced in science reporting and will concentrate on the more sensational science-related issues such as a newly found waste dump threatening a community.

Nevertheless some efforts have succeeded in placing highly accurate basic science news and features on local commercial broadcasts. Don Herbert, formerly well-known as "Mr. Wizard," has for four years been syndicating his "*HOW ABOUT...*" series to about 121 stations around the country. These stations insert his 80-sec spots into their own news. The American Institute of Physics has been working in a similar fashion for four years, producing and distributing *SCIENCE TV REPORT*, 2-min physics news features, to around 75, large-market, local commercial news programs. Both series enable science information to be seen by large numbers of viewers who would not necessarily tune in to an hour-long public TV science show.

Public TV. On the Public Broadcast System (PBS), in marked contrast to commercial TV, science remains a staple. Unfortunately, the number of viewers, in absolute numbers, is relatively low. The audiences for a high-quality prime-time science program on PBS is around 7.5–10 million viewers—two to three times smaller than for a commercial prime-time show. In 1983, even PBS's science-rich schedule revealed only a modest amount of new physics-related programs. One reason for this might be that physics is hard to sell to corporate underwriters. PBS experienced worsening financial straits in 1983 resulting from government cutbacks. Producers were obliged as never before to attract corporate sponsorships. Since basic science shows often wander into areas sensitive to big corporations, such as nuclear energy, pollution, and weaponry, it is perhaps understandable that PBS would prefer less controversial material.

For adults and high-school-age children, the acclaimed *NOVA* series and *NATIONAL GEOGRAPHIC SPECIALS* are still going strong. While an episode of *NOVA* may air at least two times a week, about 60% of a year's shows are reruns. A very notable new segment of *NOVA* in 1983 was a fascinating hour-long profile of physicist Richard Feynman. Significantly, this program received an extraordinary number of enthusiastic viewer responses. Carl Sagan's *COSMOS* series was rerun in 1983, once again providing a consistent and nourishing diet of TV physics and astronomy. There were scatterings of other science programs such as WNET's low-budget *INNOVATIONS*, as well as daytime instructional programming that is locally controlled and varies in content and quality from place to place.

For younger children, *3-2-1 CONTACT!*, of the Children's Television Workshop, is now in its fifth year and still manages to produce extremely imaginative, laboratory-tested science programs for 8–12 year olds.

Cable TV. Still seeking its role in the TV marketplace, cable TV has yet to acquire a definable personality. Cable News Network runs some science reports throughout the day. Cable Health Network does too.

Other TV Science. While 1983 was a relatively lean year for TV science, new schemes abound. The Institute of Electrical and Electronics Engineers' "Spectrum" magazine staff will serve as consultants to a yet-to-be-funded show called *TOMORROW/TODAY*. The 13-part magazine-format PBS series will be produced by KTEH of San Jose, California, and WNET, New York. The James S. McDonnell Foundation of St. Louis has granted the Smithsonian Institution and WETA-TV of Washington $3.5 million to produce *SMITHSONIAN WORLD*, again for public TV. Science will be a major component of the show which will begin airings early next year.

A big project is now underway in physical instructional TV that will be seen by undergraduates. *THE MECHANICAL UNIVERSE*, a California Institute of Technology TV physics course will be completed in 1985. It will consist of 26 half-hour video programs accompanied by printed materials. Funding of $2 million came from the Corporation for Public Broadcasting which received money from the Annenberg Foundation.

Also supported by Annenberg CPB funds is a University of Nebraska project, led by physicist Robert Fuller, that employs interactive video disks for teaching physics.

TV Audiences. How much physics and science programming should there be on TV? And who watches such programs? Some observers believe that a wide public understanding of science is unrealistic. Some believe that only a elite subgroup of "scientifically attentive" viewers will watch science shows.[3] Others feel that "public" means everyone and that the conspicuous absence of science from highly watched commercial TV is an egregious social failing.

The debate will continue and it may, with time, influence how potential funds for the popularization of science, such as from the National Science Foundation, will be spent. For 1984, however, the amount of physics and science on TV will be more an outgrowth of market forces, entertainment consideration, and corporate underwriting priorities.

David Kalson, American Institute of Physics

1. Marcel C. LaFollette, Daedalus **111**, 183 (Fall 1982).
2. George Gerbner, "Science and Scientists on the TV Screen," paper presented at the Annual Meeting of the American Association for the Advancement of Science, Toronto, 5 January 1981.
3. Jon D. Miller, Kenneth Prewitt, and Robert Pearson, "The Attitude of the U. S. Public Toward Science and Technology," National Opinion Research Center, University of Chicago, July 1980.

Science on Radio

Six years ago the American Institute of Physics inaugurated its own radio program, *SCIENCE REPORT*, with the intent to acquaint the lay public with the interests and activities of physical scientists. Today the program is flourishing and is aired on some 500 public and commercial radio stations across the country. It is the only program being broadcast devoted primarily to the physical sciences and its acceptance by stations has been enthusiastic.

The program itself was designed to be used as continuous, mainstream programming. Each four-and-a-half minute program contains two segments, each of which covers a topic that graphically demonstrates the interests and activities of physical scientists. Individual segments comprising a given program, each two-and-a-half minutes long, are as diverse as possible. A segment covering magnetic monopoles might be paired with one exploring solar collectors; one dealing with black holes would be linked with a segment on ocean tomography; and a segment dealing with nuclear medicine would be tied to a report on atmospheric low-frequency electromagnetic waves. This diversity not only heightens listener appeal but graphically demonstrates the kaleidoscopic variety of physical scientists' interests.

It is clear from the response to *SCIENCE REPORT* that radio stations and, by inference, the listeners they serve want solid, interesting reportage of science. It should be noted that an operative word here is interesting, for few if any stations will continue airing a program that is dull and listless. Care has been taken to ensure that the material is both interesting and informative.

The material is presented in an easy, understandable style, accompanied by sound effects, an identifying sound logo, voice quotes from scientists, an announcer who delivers the exposition, and an ending attribution that identifies AIP as the source of the program. This variety of sounds heightens the acoustic appeal of the program, a classic principle in radio production.

Each segment of each program relates as much as possible to a listener's interests, which includes curiosity about the world around him/her—another basic principle of audience attraction and retention. In this manner, the programs have found a niche among a wide radio audience of some several million people each week.

SCIENCE REPORT, then, is an attempt to raise the public consciousness with regard to scientific endeavors, and to document the value of science's research to the commonweal. Not the least of *SCIENCE REPORT*'s aims is to demonstrate the importance of "pure" research and the necessity of comprehending basic scientific principles. In this way, the public perception of scientists as part of our cultural heritage, not an elitist group pursuing elitist aims, is enhanced. Such understanding reduces antagonism towards science while fostering a supportive alliance between the public at large and scientists in general.

Production of *SCIENCE REPORT* indicated that scientists, too, are eager for their endeavors—their research, aims, ambitions, and results—to be comprehended by the community they live in and which, in turn, supports the scientific community. In over 300 interviews with scientists covering topics as diverse as fuel cell systems to bombardier beetles, not one scientist balked at elaborating on his or her research with the general public in view. All wanted their research portrayed in accurate terms, a goal of *SCIENCE REPORT* as well.

Of course, in two-and-a-half minutes, not every aspect of a scientist's labors can be detailed. No effort is made to do so. However, in this time, the interests and activities of a given scientist can be accurately characterized—just as a dictionary can accurately define the word "physics" in only a few words, while leaving elaboration of the topic to an encyclopedia. Such a characterization, in the time allotted, illustrates to the listening audience the substance of the physical sciences as shown through the work of the scientist being interviewed.

James Berry, American Institute of Physics

Physics in Museums

Science museums have been an integral part of the formal education experience at least since the beginning of this century. In Europe, major science museums in Munich, Paris, and London have served both as repositories of artifacts and as centers of learning. In North America, institutions such as the Smithsonian Institution and the Chicago Museum of Science & Industry have played similar roles, documenting the history of science and technology through the display of objects as well as providing a learning experience for generations of school children.

A rich new dimension to science museums was begun in the late 1960's, in particular the Exploratorium in San Francisco and the Ontario Science Centre in Toronto. Science teaching through the medium of participatory exhibits became an important part of the science museums' functions. Science museums became increasingly oriented towards "process" rather than objects. The remarkable accomplishments of science and technology were no longer passively displayed but rather dynamically demonstrated. This evolution of the traditional museum into an institution reaching beyond the limits of formal education was recognized by the physics profession in 1973. The American Association of Physics Teachers presented to Frank Oppenheimer, director of the Exploratorium, the prestigious Millikan Award.[1,2] Numerous institutions in North America have conducted studies in depth on the use of exhibits as learning tools and contributed to the continuing evolution of science museums as a significant complement to the traditional school system.[3]

In the last decade the importance of science museums as educational institutions has not diminished. At the same time, the institutions have become important, perhaps the most important institutions of public learning about science and technology. Total attendance at science museums has doubled over the last decade, although school visits have remained relatively constant. Some science museums attract five to six times as many adults as children.

Science museums have actively reached for audiences beyond the local site. The regular "outreach" programs have been an intregral part of the Lawrence Hall of Science's impact on the educational scene. Other museums have extended programs both for schools and for the public, to shopping malls, civic arenas, and trade shows. In addition, the science museums collaborate through the sharing of traveling exhibitions particularly under the auspices of the Association of Science and Technology Centres (ASTC).[4]

Science museums continue to have a preponderance of exhibits related to physics and related fields, such as astronomy and electronics. The traditional branches of classical physics—mechanics, optics, electromagnetism, acoustics, etc.—have always been richly represented in science museums. Modern physics is not unrepresented. Participatory exhibits on blackbody radiation, superconductivity, and special relativity have been installed in a few museums.

Since about the late 1970's computers have also become significant in a number of science museums, both as tools to expand the capabilities of the exhibit medium and as instruments of science worthy of understanding. In addition to computer science, such fields as robotics and artificial intelligence will probably dominate the present museums for the decade ahead.

Eustace Mendis, Ontario Science Centre

1. Frank Oppenheimer, Am. J. Phys. **41**, 1310 (1973).
2. Frank Oppenheimer, Am. J. Phys. **42**, 531 (1974).
3. Minda Borun, *Measuring the Immeasurable. A Plot Study of Museum Effectiveness* (Association of Science and Technology Centers, Washington, D.C., 1977).
4. Association of Science and Technology Centres, 1016 16th St., N. W., Washington,
D.C. 20036.

ELECTRON AND ATOMIC PHYSICS

The study of atoms and molecules has been at the heart of 20th-century physics. Higher accelerator energies have permitted the exploration of matter at ever smaller scales—the nucleus, the proton, and now quarks—but a careful analysis of atomic and molecular dynamics is still essential.

Atomic research has been revitalized by the advent of new experimental techniques. The use of lasers is widespread, particularly high-powered solid-state lasers, tunable dye lasers, and lasers at ultraviolet wavelengths. New accelerators dedicated to the product of synchrotron radiation are providing high-powered beams over a wide range of wavelengths. Computers and new detectors have streamlined data taking.

Bell's Inequality and Experimental Tests of Quantum Mechanics

Recent atomic physics experiments have made a definitive contribution to our understanding and interpretation of quantum mechanics. It is generally accepted that quantum mechanics makes statistical predictions that are in excellent agreement with experimental data. The interpretation of quantum mechanics for single microscopic events has, however, been the subject of widespread controversy. The focal point for this controversy in a classic paper by Einstein, Podolsky, and Rosen[1] in which they put forth the proposition that quantum mechanics is an incomplete theory. To complete the theory, additional variables would presumably be required, and the term "hidden variables" was eventually coined for them. These hidden variables would enable one to make precise, deterministic predictions at the microscopic level. For example, if a vertically polarized light beam is incident on a linear polarizer whose transmission direction is at 45° to the vertical, then quantum mechanics can only tell us that the probability each photon will be transmitted is 50%; however, if one knew the values of these proposed hidden variables, then for each photon one could predict with certainty (100% probability) whether or not it would be transmitted.

A milestone in the interpretation of quantum mechanics was the proof in 1965 by J. S. Bell[2] that no theory incorporating hidden variables and satisfying a physically reasonable condition of locality (a "local hidden variable theory") could reproduce all the statistical predictions of quantum mechanics. The proof involves studies of correlated systems and takes the form of an inequality which must be satisfied by the statistical results of any local hidden variable theory, but which may be violated in some situations by the statistical predictions of quantum mechanics.

The locality condition simply states that the effects produced by an analyzer or detector should be independent of the settings of other spatially separated analyzers and detectors. Physically, the Bell inequalities tell us that in any local hidden variable theory there is a limit on the strength of the correlations that may be observed in an experiment; in contrast, quantum mechanics predicts very strong correlations that may exceed that limit.

Bell's inequalities made it possible to test the validity of the entire class of local hidden variable theories by performing experiments in which the quantum mechanical predications violate them.[3,4] At present, the most definitive experiments are those involving observation of polarization correlations between two photons in an atomic cascade. The consensus of these experiments is that any local hidden variable theory is inconsistent with nature. The first of these experiments was performed in 1972 by Freedman and Clauser[5] using a cascade in calcium. The initial state of their cascade had zero total angular momentum ($J = 0$) and the intermediate state was very short lived (5 nsec). In 1976, Fry and Thompson[6] completed an experiment on ^{202}Hg with an initial state of total angular momentum $J = 1$ and a relatively long-lived intermediate state (120 nsec). They obtained a dramatic relative improvement in the available signal using a laser excitation scheme. This was especially important for examining systematics, which almost invariably weaken the correlation and lead to results satisfying the inequalities.

In the last two years, the original Freedman and Clauser experiment has been repeated by a group in France, but with several important variations and improvements.[7–9] First, they used a two-photon laser excitation scheme that dramatically improved again the signal-to-noise ratio. Second, they tested the inequality for various source-polarizer separations up to 6.5 m. Third, they did an experiment with two-channel linear polarizers (i.e., both orthogonal linear polarization signals were observed at each cascade wavelength). This enabled them to obtain the strongest violation of a Bell inequality ever observed. Fourth, they performed an experiment using time-varying polarizers in which the effective polarizer orientation is chosen in a time less than that required for a light signal to travel between the two analyzer systems for the two cascade wavelengths. This experiment did not rigorously satisfy Einstein locality, since the choice was made quasiperiodically rather than randomly; nevertheless, it provided an important step beyond the fixed polarizers of all previous experiments. In all the experiments performed by the French group, excellent agreement with quantum mechanical predictions and clear violation of the Bell inequalities was observed.

Small loopholes still exist, but the overwhelming evidence provided by these atomic cascade experiments stands against any theory that would supplement quantum mechanics with hidden variables and still retain the physically very reasonable condition of locality.

Edward Fry, Texas A & M

1. A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).
2. J. S. Bell, Physics **1**, 195 (1965).
3. J. F. Clauser and A. Shimony, Rep. Prog. Phys. **41**, 1881 (1978).
4. B. d'Espagnat, Sci. Am. **241**, 158 (November 1979).
5. S. J. Freedman and J. F. Clauser, Phys. Rev. Lett. **28**, 938 (1972).
6. E. S. Fry and R. C. Thompson, Phys. Rev. Lett. **37**, 465 (1976).
7. A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. **47**, 460 (1981).
8. A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. **49**, 91 (1982).
9. A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. **49**, 1804 (1982).

Laser Cooling of Atomic Beams

Atoms and molecules in a gas such as air are in a constant state of motion, having velocities near the speed of sound. They make frequent collisions with other atoms and molecules, changing their velocities and other basic properties as well. Such a jumbled collection of atoms is often unsuitable for high-precision experiments.

To overcome these problems, researchers often create atomic beams, streams of atoms all going in the same direction through a vacuum. While this is a distinct improvement over a gas, the atoms in the beam are still moving very rapidly and with a wide range of speeds. This thermal motion (the motion of atoms relative to one another) is often a serious impediment to making precise and accurate measurements on the atoms. For example, the frequency of light emitted by a moving atom is Doppler shifted in much the same way as the pitch of a train whistle is shifted as it moves past a listener. In addition, the moving atoms can only be observed for a short period of time, which further limits the precision of the measurements performed on them.

The development of powerful tunable lasers has opened the possibility of applying very strong forces to atoms. If the energy of the photons in the laser beam exactly corresponds to the separation of energy levels in the atoms the ensuing resonance results in a large radiation pressure force. For sodium atoms, the force can be 100,000 times larger than that of gravity.

In 1975 Hänsch and Schawlow showed how the radiation pressure could be used to "cool" or reduce the thermal motion of atoms.[1] In 1978 this idea was used by groups at the National Bureau of Standards in Colorado and at Heidelberg University in West Germany to cool electrically charged ions stored in a trap.[2] Although other researchers attempted to slow down a beam of electrically neutral atoms, this proved to be more difficult than cooling trapped ions. The difficulty stems mainly from the short time available (msec) to cool a beam before it reaches the end of a laboratory-size vacuum chamber, compared to the storage time for trapped ions (days). This means that the cooling must be very efficient. A major source of inefficiency comes from the variation of the Doppler shift—to the decelerating atoms the laser frequency and thus the photon energy appears to be changing. Since the maximum light pressure is exerted only when the atom and photons match, the force is not sufficient to significantly slow the atoms unless one can compensate for this varying Doppler shift.

A group at the Institute of Spectroscopy in Moscow has demonstrated laser cooling of an atomic beam, but with only a small deceleration because of the changing Doppler shift.[3]

Recently, a group at the National Bureau of Standards in Maryland has succeeded in dramatically reducing the atomic velocity by compensating for the changing Doppler shift as the atoms decelerate. In this experiment a strong laser beam is directed exactly opposite to the direction the atoms are moving, so that the radiation pressure slows them down.[4] To compensate for the changing Doppler shift, the NBS group used a spatially varying magnetic field which shifted the energy levels of the atoms so as to cancel the change in Doppler shift. Another method used by the NBS group involves changing the frequency of the laser, rather than shifting the energy levels of the atoms, to compensate for the changing Doppler shift. Both techniques produce substantial cooling of the atomic beam.

Using the varying magnetic field technique, the atoms were brought nearly to rest (4% of their initial velocity) in a distance of less than a meter. Not only are the atoms slowed down, but they are nearly all slowed down to the same velocity. The spread of velocities in the cooled beam is like that of a gas whose temperature is less than a tenth of a degree above absolute zero. If any ordinary gas were refrigerated to such a low temperature, it would liquify or solidify. Thus, the cold atomic beam is a truly unique tool for studying free atoms.

A possible application of this new atomic beam technique is ultrahigh resolution spectroscopy, the very precise measurement of the energy levels of atoms. The best of such measurements are now limited by the motion of the atoms.[5] Other applications include studies of the statistical nature of the interaction of light with matter[6] and studies of atomic collisions under very well-controlled conditions. A particularly exciting application is the possibility of delivering very low-energy neutral atoms for the purpose of trapping them in electromagnetic fields. Such traps have long been proposed, but never successfully operated, because until now no atoms with low enough energy to stay in the trap have been available.

W. D. Phillips, National Bureau of Standards

1. T. W. Hänsch and A. Schawlow, Opt. Commun. **13**, 68 (1975).
2. *Physics News in 1978*, p. 22.
3. S. V. Andreev, V. I. Balykin, V. S. Letokhov, and V. G. Minogin, JETP Lett. **34**, 442 (1981).
4. J. V. Prodan, W. D. Phillips, and H. J. Metcalf, Phys. Rev. Lett. **49**, 1149 (1982); Arthur L. Robinson, Science **218**, 1103 (1982).
5. Ch. Salomon, Ch. Breant, C. J. Borde, and R. L. Banger, J. Phys. (Paris) **42**, C8 (1981).
6. R. J. Cook, Opt. Commun. **35**, 347 (1981).

Coulomb Explosions

Although fast (MeV) molecular-ion beams have been used for many years in the energy calibration of nuclear accelerators, it was not until quite recently that experimenters began to take advantage of the spatial and temporal correlation of the nuclei constituting the molecular projectiles.[1]

When light diatomic projectiles (H_2^+, HeH^+, $^3He_2^+$) are incident at MeV energies upon a foil, the electrons bound to the projectile molecules are almost always totally stripped off within the first few angstroms of penetration into the solid target. This leaves two bare (or nearly bare) nuclei which rapidly separate owing to their mutual Coulomb repulsion. This violent dissociation process, in which the initial electrostatic potential energy is converted into kinetic energy of relative motion, has been termed a "Coulomb explosion."

The characteristic time for this explosion is typically a femtosecond (10^{-15} sec). In comparison, typical periods for molecular vibrations (10^{-14} sec) and rotations (10^{-12} sec) are so much longer that the outgoing fragment trajectories are determined solely by the Coulomb energy of the exploding molecule. The explosion time is on the same order of magnitude as the dwell time of the projectile in the thin (100 Å) foil target. As a result, much of the Coulomb explosion takes place inside the foil.

Emerging from the foil, one has fragments with both the original beam velocity and a component from the Coulomb explosion. This component causes a shift in the laboratory energy and angle of each fragment; the amount of this shift depends on the orientation of the incoming molecule. Because all orientations are populated in the incident beam, joint distributions in energy and angle for the emerging fragments are ringlike. The diameter of the ring is determined primarily by the bond length in the incoming projectiles, while the "thickness" of the ring is a reflection of the vibrational excitation of the incident molecules. The distribution of particle intensity around the ring is a sensitive probe of the electron–plasma oscillations generated in the target by the passage of the charged projectiles.[2]

In recent years, several experimental groups have exploited these techniques to study the structures of "normal" molecular ions. The first experimental confirmation of the equilateral structure of the H_3^+ ion, the simplest polyatomic molecular ion, was one result.[3]

Within the past year, certain results from these experiments have led experimenters to focus attention on exotic electronic states of both the molecules and the Coulomb-explosion fragments. At both Argonne and the Weizmann Institute, evidence had been mounting which suggested that Rydberg (highly excited) states of the molecular cluster exiting the foil play an important role in the formation of rare charge states of the Coulomb explosion fragments. Such highly excited molecules, with one electron orbiting at large (sometimes macroscopic) distances from the molecular core, are analogous to Rydberg atoms and have some remarkable properties. Rydberg atoms have very long radiative lifetimes and thus seldom decay without external perturbations. They are, however, very sensitive to even weak external electromagnetic fields. An understanding of the formation and decay of Rydberg atoms is central to the study of subjects such as fusion plasmas, interstellar clouds and the solar corona.

The experiments at Argonne have now demonstrated that Rydberg atoms can be formed in large numbers by passing fast ions through thin carbon foils. In those experiments, Rydberg atoms were detected by observing the electrons produced by electric field ionization of the fast-moving atoms. This technique allows the application of fairly weak electric fields which in turn makes it possible to study extremely high regions of excitation.[4]

During 1983 a group in Lyon has used the Coulomb explosion technique to demonstrate that the neutral H_3 molecule, which is unstable in its ground state, lives longer than 3 μs when it is in one of the excited Rydberg states. Such H_3 molecules are formed by passing a beam of H_3^+ ions through a gas and Coulomb explosion in solid foils is used to separate the neutral H_3 molecules from the HD contaminant, which has plagued earlier attempts to detect the exotic molecule H_3.

D. S. Gemmell and E. P. Kanter, Argonne

1. Phys. Today **32**, 17 (May 1979).
2. Z. Vager and D. S. Gemmell, Phys. Rev. Lett. **37**, 1352 (1976)
3. M. J. Gaillard *et al.*, Phys. Rev. A **17**, 1797 (1978).
4. Z. Vager, B. J. Zabransky, D. Schneider, E. P. Kanter, Gu Yuan Zhuang, and D. S. Gemmell, Phys. Rev. Lett. **48**, 592 (1982).

Electron–Positron Scattering Comparisons

The development of slow positron beams in recent years has provided fresh opportunities for testing electron–atom scattering theories. Such theories are of considerable importance to many areas of science and technology, such as plasma physics, laser development, gaseous electronics, astrophysics, and aeronomy. Since positrons, the antiparticles of electrons, differ from electrons only by the sign of their electric charge, comparison measurements (hereafter denoted by $e^{+,-}$) of the scattering of positrons and electrons by the same atoms and molecules can reveal interesting differences and similarities that arise from the basic interactions (static, polarization, and exchange) contributing to $e^{+,-}$ scattering.[1]

Comparison total cross-section measurements have recently been reported by a group at Wayne State University for $e^{+,-}$ scattering from inert gases[2,3] and several simple molecules (H_2, N_2, CO, and CO_2).[4,5] They found that the total scattering cross sections for a given target were larger for the electrons than for the positrons, although the two grew closer at the highest energies investigated, implying that at sufficiently high energies only the static interaction, which arises from the interaction of the projectile particle with the Coulomb field of the undistorted atom, is important.

At lower energies, the polarization interaction, resulting from the distortion of the target atom by the passing projectile, tends to cancel the effect of the static interaction for positrons, but enhances the effect for electrons.

Finally, the exchange interaction, which arises from the indistinguishability of a projectile electron from electrons in the target atom, contributed only to electron scattering.

In the case of scattering from helium, it has been observed[2] that the e^+ and e^- total cross sections converge (to within 2%) for energies above 200 eV. At lower energies, the cross section for electrons exceeds that for positrons by more than a factor of 100.[6] The convergence above 200 eV is a particularly interesting result because the best available theories predict that it should occur at a much higher projectile energy.[7]

The maxima of the cross section curves for electrons are associated with elastic scattering, while for positrons, the maxima occur at somewhat higher energies than for electrons and appear to be dominated by inelastic processes, such as the formation of positronium, the short-lived state consisting of an electron and positron bound together.[1]

W. E. Kauppila and T. S. Stein, Wayne State University

1. T. S. Stein and W. E. Kauppila, Adv. Atom. Mol. Phys. **18**, 53 (1982).
2. W. E. Kauppila *et al.*, Phys. Rev. A **24**, 725 (1981).
3. M. S. Dababneh *et al.*, Phys. Rev. A **26**, 1252 (1982).
4. K. R. Hoffman *et al.*, Phys. Rev. A **25**, 1393 (1982).
5. Ch. K. Kwan, *et al.*, Phys. Rev. A **27**, 1328 (1983).
6. T. S. Stein *et al.*, Phys. Rev. A **17**, 1600 (1978).
7. D. P. Dewangen and H. R. J. Walters, J. Phys. B **10**, 637 (1977).

The Transfer of Atoms Between Molecules

Among the several achievements for which L. H. Thomas was awarded the 1981 Davisson–Germer Prize was his 1927 classical theory[1] of capture of electrons from atoms by incoming positive ions, a remarkably prescient theory whose quantum mechanical validity in certain high-velocity limits was not properly appreciated until a few years ago.[2] Only in 1983 has the so-called Thomas double scattering peak been observed in the angular distribution of projectiles following electron pickup from a target atom.[3] This direct experimental test had been missing owing to the supreme difficulty of isolating the Thomas peak at millidegree angles in scattering experiments. The small electron–nucleus mass ratio is at the heart of the difficulty.

The Thomas double scattering peak was actually seen clearly in 1975 in an ion–molecule reaction in which the formation of the hydrogen molecular ion H_2^+ following proton impact on methane was observed.[4] Stimulated by a 1964 paper by Bates and collaborators who applied Thomas' method,[5] Cook, Smyth, and Heinz discovered a broad peak in H_2^+ production at an angle of about 45° to the incident proton direction. The peak arises in a two step, double scattering process. First, the incident proton knocks the target hydrogen atom toward the carbon nucleus in methane (CH_4), which then scatters elastically from the carbon nucleus through about 90° in such a way that both the incident proton and the struck atom emerge with about the same speed and direction, so that sticking together to form H_2^+ is a likely event. Because the incident and struck particles have similar mass, the Thomas angle is much larger for atom capture from a molecule than it is for electron capture from an atom.

Also seen for the first time in 1981 was the related process of atom capture to the continuum, i.e., the creation of an unbound molecular ion state having a positive energy lying just above the dissociation limit.[6] This recently discovered process was discussed twice in *Physics News in 1979*, once for electron capture to unbound states of projectile ions,[7] and once for capture of negative pions created by heavy ions[8] in collisions with target nuclei. In all cases, the target particle is captured by the projectile, which it accompanies thereafter without being actually bound to it. This means that the capturing and captured particle are free to drift apart slowly after the capture event.

Although the atom capture experiments are carried out at energies of only about 100 eV per nucleon relative to the initial speed of the captured particle in the target molecule, the projectile velocity is much faster than in analogous electron capture at many MeV per nucleon. Because atoms vibrate much more slowly in molecules than do individual electrons in atoms, it is possible to test the high-velocity limits of scattering theory much more stringently at 100-eV-per-nucleon energies in ion–molecule reactions than in 10-MeV-per-nucleon electron capture experiments.

Ivan Sellin, University of Tennessee

1. L. H. Thomas, Proc. R. Soc. London, Ser. A **114**, 561 (1927).
2. R. Shakeshaft and L. Spruch, Rev. Mod. Phys. **51**, 369 (1979).
3. E. Horsdal-Pedersen, C. L. Cocke, and M. Stockli, Phys. Rev. Lett. **50**, 1910 (1983).
4. C. J. Cook, N. R. A. Smyth, and O. Heinz, J. Am. Phys. **63**, 1218 (1975).
5. D. R. Bates, C. J. Cook, and F. J. Smith, Proc. Phys. Soc. **83**, 49 (1964).
6. M. Breinig, G. J. Dixon, P. Engar, S. B. Elston, and I. A. Sellin, Phys. Rev. Lett. (to be published); M. Breinig and I. A. Sellin, Bull. Am. Phys. Soc. **26**, 601 (1981).
7. *Physics News in 1979*, p. 25.
8. *Physics News in 1979*, p. 68.

Dielectronic Recombination

The distribution of ion charge states in a hot plasma, such as those found in a stellar corona or a fusion reactor, depends upon the competing rates of ionization and recombination. When an unbound electron recombines with an ion, the extra energy must be removed in some way. Two processes are known to be important in recombination: radiative recombination, in which a photon is released whose energy exactly equals the energy loss; and dielectronic recombination (DR), in which an unbound electron of just the right energy excites a previously bound electron and in so doing is captured into a bound state. The latter process results in a doubly excited ion, which eventually stabilizes by either autoionizing or by emitting a photon.

Dielectronic recombination rates can be orders of magnitude larger than simple radiative recombination rates, especially for multiply charged ions.[1] Radiative losses from plasmas owing to DR can be quite high; but of even greater importance is the fact that DR strongly influences the equilibrium charge state distributions of the ions. Therefore, dielectronic recombination cross sections must be accurately known in order to model high-temperature plasma correctly. Radiation arising from DR is observable in plasma experiments and the spectra obtained have been used to adduce DR rates.[2] However, because it is difficult to shoot electrons of the required low energy at ions which have a controlled velocity, there had been, until 1983, no reported measurements of DR cross sections.

All of a sudden, this year, three experimental groups reported success in measuring DR by making an electron beam collide with an ion beam. Merged electron–ion beam techniques were used by groups at Oak Ridge National Laboratory[3] and at the University of Western Ontario.[4] By merging two collinear beams, very low relative energies can be obtained. The Ontario group studied DR in C^+ by merging a 450-keV C^+ beam with an electron beam to achieve collision energies of 8–10 eV, while the ORNL group, using 15–25-MeV beams of B^{2+} and C^{3+} merged with an electron beam, was able to study DR in multiply charged ions at collision energies of 2–20 eV.[5] A group at the Joint Institute of Laboratory Astrophysics measured the DR cross section for Mg^+ ions using a crossed electron–ion beam technique. Coincidences between recombined neutral Mg atoms and photons were measured as a function of electron energy.

Detailed calculations on the B^{2+} and C^{3+} systems[6] were in reasonable accord with the Oak Ridge results; the other experiments, however, indicated significantly higher cross sections than predicted. The cross section obtained in an experiment on Mg^+ was approximately six times larger than theory.[6] This may be due to a heretofore unsuspected effect of electric fields on the mixing of angular momentum states in the doubly excited recombined ion.[7]

Sheldon Datz, Oak Ridge National Laboratory

1. J. Dubau and S. Volonte, Rep. Prog. Phys. **43**, 200 (1980).
2. M. Bitter *et al.*, Phys. Rev. Lett. **43**, 129 (1979).
3. P. Dittner, S. Datz, P. D. Miller, C. D. Moak, P. H. Stelson, C. Bottcher, G. D. Alton, W. B. Dress, and N. Neskovic, Phys. Rev. Lett. **51**, 31 (1983).
4. J. B. A. Mitchell, C. T. Ng, J. L. Forand, D. P. Levac, R. E. Mitchell, A. Sen, and J. Wm. McGowan, Phys. Rev. Lett. **50**, 335 (1983).
5. D. McLaughlin and Y. Hahn, Phys. Rev. A **27**, 1389 (1983).
6. D. S. Belic, G. H. Dunn, T. J. Morgan, D. W. Mueller, and C. Timmer, Phys. Rev. Lett. **50**, 339 (1983).
7. K. LaGattuta and Y. Hahn, Phys. Rev. Lett. (in press).

ELEMENTARY PARTICLE PHYSICS

Elementary particle physics is the study of the structure of matter at the smallest scale. Since fine structure is best revealed by performing scattering experiments, this scale is reduced every time particle beam energies are increased. Thus, the evolution of powerful particle accelerators has resolved successively atoms into nuclei and electrons, nuclei into protons and neutrons, and most recently, protons into quarks.

Some big pieces in the particle physics jigsaw puzzle fell neatly into place last year. The discovery at CERN of the *W* and *Z* particles, the carriers of the weak nuclear force, was the best support yet for the Weinberg–Salam–Glashow model, a theory which mathematically comprises the weak and electromagnetic forces into a single electroweak force.

The first direct observation of the *B* meson, a particle with a nonzero "bottom" quantum number, helped to support the hypothesis that quarks come in six flavors. Bottom (or sometimes "beauty") is the name for the fifth quark flavor. The sixth quark, presumably heavier than all the others, has not yet been observed, although some believe that the high-energy, proton–antiproton collision data recorded at CERN in pursuit of the *W* particle may also harbor evidence for the top quark.

The general thrust of theoretical work in particle physics is the effort to synthesize descriptions of the four physical forces into a single all-encompassing model. The union of the weak and electromagnetic forces seems secure. The job of yoking this combined electroweak force with the strong force—the force between the quarks—has proved more difficult. Already the simplest version of a "grand unified theory," known as SU(5), is running into trouble. An estimate of the proton's lifetime based on this theory is at variance with the experimental results from a specially built detector isolated far underground. After more than a year of data taking, this detector has recorded not a single proton decay.

Besides the subjects examined in the articles that follow, there were several areas of interest in particle physics over the past year. The search for neutrino oscillation (one neutrino turning into another) and neutrino mass continues to be frustrating. An experiment using a nuclear reactor in Switzerland reports no evidence for oscillation.[1] A group from Moscow, claiming a few years ago to have measured a nonzero neutrino mass (see *Physics News in 1981*, p. 47), published a new lower limit of 20 eV for the mass of the electron neutrino.[2]

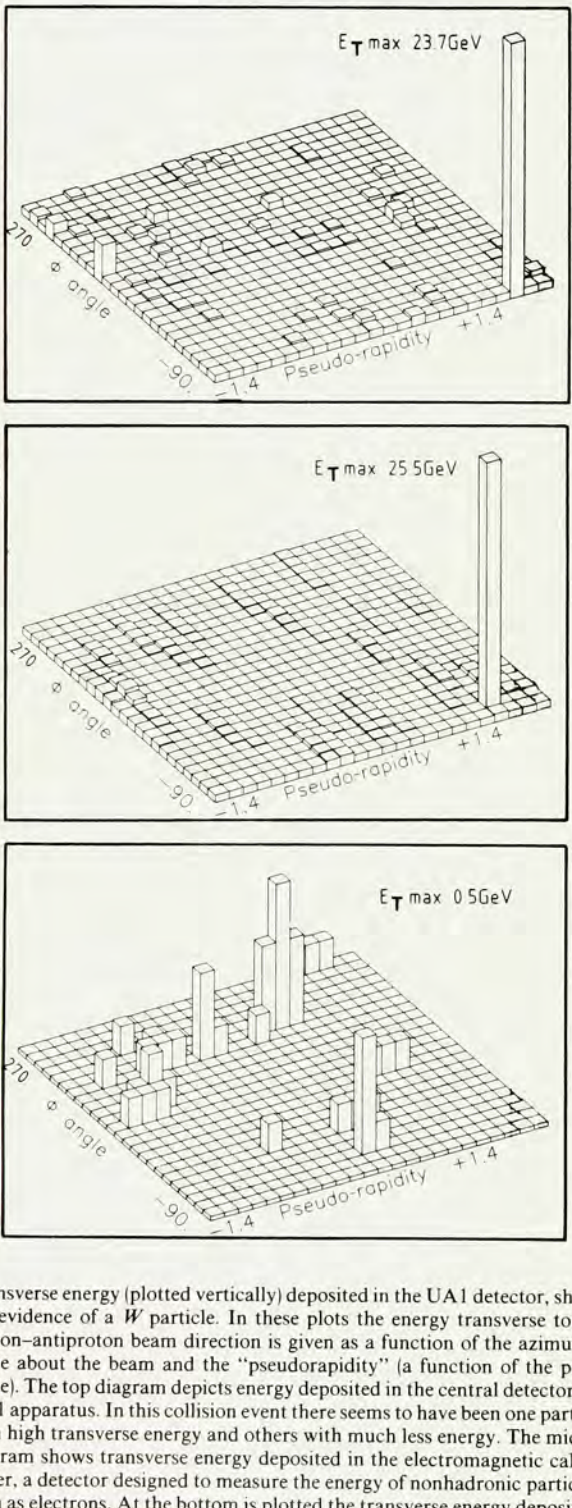
Deep inelastic scattering is the scattering of a lepton (electron, muon, or neutrino) from a nucleon (a proton or neutron inside an atomic nucleus) in which numerous additional particles are produced as a byproduct. Deep inelastic scattering can provide information about how quarks disport themselves inside the nucleon when due allowance is made for the fact that the nucleon itself is moving about (Fermi motion) inside the nucleus. Recent comparison between muon–iron and muon–deuterium scattering at CERN and electron–deuterium and electron–aluminum scattering performed at SLAC in 1972 has shown that the quark structure functions (functions that describe quark behavior inside the nucleon) vary from iron to aluminum to deuterium, and in a way which is opposite to what one would expect from Fermi-motion effects.[3] This strange effect is interpreted by some as evidence for six-quark states within nuclei.

Phillip F. Schewe

1. New Scientist **98**, 219 (28 April 1983).
2. Cern Courier **23**, 250 (September 1983).
3. Cern Courier **23**, 91 (April 1983); **23**, 261 (September 1983).

Intermediate Vector Bosons

The intermediate vector bosons, the supposed carriers of the weak nuclear force, have finally been observed at the CERN accelerator in Geneva, Switzerland, lending major support to unified theories of particle interactions. Carlo Rubbia of Harvard, leader of the 126-physicist UA1 collaboration,[1] and Pierre Durriulat of CERN, leader of the 51-physicist UA2 collaboration,[2] reported at first the observation of only a handful of events in which the charged intermediate bosons, the W^+ and W^-, were created. Several months later, after more data taking, the sample of observed W particle events had increased to about 90, and the Z^0, the neutral cousin of the W, had also been observed.[3]



Transverse energy (plotted vertically) deposited in the UA1 detector, showing evidence of a W particle. In these plots the energy transverse to the proton–antiproton beam direction is given as a function of the azimuthal angle about the beam and the "pseudorapidity" (a function of the polar angle). The top diagram depicts energy deposited in the central detector the UA1 apparatus. In this collision event there seems to have been one particle with high transverse energy and others with much less energy. The middle diagram shows transverse energy deposited in the electromagnetic calorimeter, a detector designed to measure the energy of nonhadronic particles, such as electrons. At the bottom is plotted the transverse energy deposition by hadrons, such as pions. The low energy deposited by hadrons, and the presence of a high-energy electron identify this as a W-particle candidate event.

At CERN beams of protons and antiprotons collide head on at a total energy of 540 GeV (540-billion eV). This impact energy can be converted into exotic, short-lived particles which would not ordinarily be seen in normal matter. The W particle, produced in this way, plays a crucial role in the theory that unites into one mathematical framework the weak and electromagnetic forces. Although these two forces are now very different in their effect—the electromagnetic force holds atoms together and is responsible for all electronic phenomena, while the weak force causes certain kinds of radioactivity and also mediates some of the combustion reactions in the sun—it is thought that in the earlier, hotter universe they were both manifestations of a single "electroweak" force. And just as the photon propagates the electromagnetic force, so it was thought that the weak force should also employ a courier particle; actually three particles would be needed: the W^+, W^-, and Z^0 mesons, also known as intermediate vector bosons.

The electroweak theory not only calls for these particles, but specifies what their mass should be, roughly 80 GeV, or about 80 times the mass of the proton. This accounts for the weakness of the weak interactions: the W's large mass makes it difficult to produce and its range short. What the experiments at CERN create in the instant that a proton and antiproton collide head on at 540 GeV is, in effect, a tiny piece of the early universe; the conditions at the point of impact resemble those that prevailed less than a second after the big bang, a time when W particles could be easily produced, making the weak force comparable to the electromagnetic force.

The accelerator at CERN was specially adapted to look for particles like the W.[4] During a 30-day running period in November and December of 1982, the two separate detector groups UA1 and UA2 (short for Underground Areas One and Two) each observed about a billion proton–antiproton collisions. Of these, about a million select events were recorded, and of these only a handful survived the painstaking data analysis designed to discard all but a very special kind of occurrence, one in which the incoming proton and antiproton obliterate to form a W particle (plus various hadrons) which decays almost immediately into an electron and a neutrino. The crucial criteria for selecting such an event are: (1) that the electron emerge from the W-decay region with a large momentum in a direction transverse to the beam axis; (2) that the amount of transverse momentum carried away by the hadrons be relatively small; and (3) that there be a conspicuous lack of transverse momentum for particles traveling in a direction opposite the electron.[5] The missing momentum is presumably carried by the neutrino, the other product of the W decay. The neutrino is not observed directly, but its properties can be inferred from the energy imbalance left over after accounting for all the other particles.

The Z^0 events were those in which a high-energy electron and positron (the product of Z^0 decay) emerged at 180° relative to each other and also transverse to the beam axis. Muon–antimuon pairs fitting this description may also have arisen from Z^0 decay.

By July[6] the tally of events and experimentally determined particle masses for the two detector groups looked like this: For the W particle, UA1 (55 events) and UA2 (35 events) both find a mass of 81 GeV, very close to the theoretical (Weinberg–Salam–Glashow model) estimate of 83 GeV. For the Z^0, UA1 (six events) finds a mass of 95.2 GeV, UA2 (four events) finds 91.2 GeV, and theory gives 93.8 GeV. More data will eventually allow a better determination of the masses.

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1. G. Annison *et al.*, Phys. Lett. B **122**, 103 (1983).
2. M. Banner *et al.*, Phys. Lett. B **122**, 476 (1983).
3. G. Annison *et al.*, Phys. Lett. B **126**, 398 (1983).
4. David Cline, Carlo Rubbia, and Simon Vander Meer, Sci. Am. **246**, 48 (March 1983).
5. Phys. Today **36**, 17 (April 1983).
6. Science **221**, 840 (26 August 1983).

The Salt Mine Detector

A salt mine 2000 ft beneath Cleveland is the preserve of one of the most elaborate hunts in physics research, the search for decaying protons. Using a vast detector—essentially a cube of water (8000 tons) the size of a six-story building—a team of scientists from Irvine (University of California), Michigan, and Brookhaven National Laboratory have seen no evidence for the decay of the proton into a positron and neutral pion, the most likely decay route.

To observe something as rare as proton decay, you must watch a large sample of protons (in this case, those bound up in water molecules) for a long time. An early report on the salt mine detector considered a data logging period of eighty days, a body of data equivalent to 700 ton-years.[1] This is to be compared with ongoing experiments in India (100 ton-yr so far) and under Mt. Blanc in the Alps (also 100 ton-yr).[2] The IMB collaboration sees no decay events, the Indian experiment has recorded three (candidate events), and Mt. Blanc one.

This paucity of events does not mean that the proton does not decay. Nor does it mean that the Grand Unified Theory (GUT), which postulates proton decay, must be discarded. It does imply that the simplest version of the unified theory, known as SU(5), is probably a bit too simple. SU(5), for instance, prescribes that the proton should have an average lifetime of *no greater than* about 2.5×10^{31} yr. The IMB results necessitate a lifetime of *more than* 6.5×10^{31} yr.

In order to unite the strong force with the electroweak force (itself a marriage of the electromagnetic and weak forces), GUT theorists prescribe the existence of a massive (10^{15} GeV) X boson with the ability to turn quarks into leptons and vice versa. Although such a particle is much too heavy to create artificially in any accelerator, its effects could occasionally be felt. The decay of the proton is just such an effect.

In one typical scheme, the proton decays into a neutral pion and a positron. To see how this happens, imagine a proton as consisting of two up quarks and one down quark. One of the up quarks emits an *X* boson and converts into an anti-up quark. (The rarity of this phenomenon accounts for the proton's great stability.) The *X* boson is quickly absorbed by the down quark, transforming it into a positron. Meanwhile, the anti-up quark combines with the leftover up quark to form the pion. The pion itself decays into two high-energy photons (gamma rays).

The decay mode $p\rightarrow e^{+}\pi^{0}$ should account for about 40% of all proton decays.[3] For this type of decay, the IMB works in the following way: The positron and the two gammas from the pion decay produce characteristic Cherenkov radiation (the optical analog of a sonic shock wave) as they speed through the ultrapure water of the detector vessel. This radiation is then detected in an array of 2000 phototubes deployed around the edge of the water volume. The location of the decay can be reconstructed from the distribution of hits recorded in the tubes, while the energy of the decay products can be calculated from the integrated number of photoelectrons engendered in the tubes.

There are other conceivable proton decay routes, such as the decay into an antineutrino and a charged pion (with a branching ratio of 16%), and other lesser likely modes. Because there are different decay scenarios it is useful to quote the experimentally determined lifetime (or if, as in this case, no decays have been observed, a lower limit on the lifetime) divided by the appropriate branching ratio. Thus for the most recent report on the IMB efforts, based on 130 days of running time, the ratio T/B for the $p\rightarrow e^{+}\pi^{0}$ mode is calculated at greater than 10^{32} yr.[1]

The detector scheme used in Cleveland also makes possible a search for other interesting phenomena. Neutron oscillation, the hypothetical transformation of a neutron (in one of the atoms in the water molecules) into an antineutron and vice versa is, like proton decay, an exotic reaction permitted by some GUT models. The appearance of an antineutron in the vicinity of a neutron could result in mutual annihilation and a characteristic burst of light. The IMB detector group sees no evidence for neutron oscillation and can place a limit on the frequency of its occurrence that is as stringent as any of the oscillation experiments conducted so far at nuclear reactors.

GUT models also allow for the existence of magnetic monopoles. In one scenario a slow-moving monopole can "catalyze" a series of proton decays in its wake as it passes through matter. No such decays were seen, and again, as with proton decays and neutron oscillations, the absence of pertinent events served to constrain somewhat the bounds within which a grand unified theory could unfold.

Phillip F. Schewe

1. R. Bionta *et al.*, Phys. Rev. Lett. **51**, 27 (1983).
2. G. Battistone *et al.*, Phys. Rev. Lett. B **118**, 491 (1982).
3. Phys. Today **36**, 20 (September 1983).

B Meson

The *B* meson, a particle containing a "bottom" quark along with an ordinary quark, has been observed at the Cornell Electron Synchrotron Ring (CESR), by a collaboration consisting of 79 physicists from eight institutions.[1]

In 1974 the discovery of the psi meson by groups at Stanford and Brookhaven opened an active period in the search for new particles. The psi was deemed to consist of two new quarks: charm and anticharm. Charm thus became the fourth "flavor" of quark; the more traditional denominations were known as up, down, and strange. The psi itself is without charm, but soon daughter particles (the result of psi decay), known as *D* mesons, with a net value of charm, were discovered. These particles contain charm quarks mated with noncharm quarks (up, down, and strange).

In 1977 the upsilon was discovered. The upsilon is a particle analogous to the psi made from another pair of new quarks: bottom and antibottom. Bottom is the fifth quark flavor. The *B* mesons are to the upsilon what the *D* mesons are to the psi. Their discovery helps to support the "standard model" which calls for six quark flavors. Evidence for the sixth quark, the top quark, has not yet been found (see the accompanying article).

The *B* mesons are produced in the following manner[2]: At CESR beams of high-energy electrons and positrons collide head on, producing the upsilon triple prime (the fourth and heaviest of the upsilons) which decays into a *B* and anti-*B* meson. These particles decay quickly too, but their existence and their properties can be inferred from their decay products. Typically, a B^{-} meson should decay into a D^{0} and π^{-}. The D^{0} in turn decays into a K^{-} and π^{+}. Finally the K^{-} decays into an antineutrino, a positron, and a neutral pion.

The upsilon triple prime was first seen in 1980 (see *Physics News in 1980*, p. 45). At that time it was suspected that this particle, unlike the lighter upsilons, was massive enough to give birth to a pair of *B* mesons.[3] The complexity of sorting out the various decay products prevented direct observation of the *B* mesons and an accurate mass determination until the present experiment. In the first report[1] 18 *B* meson events were sifted from a sample of 140,000 recorded events. Of these 18 events, nine corresponded to neutral *B*'s and nine to charged *B*'s. The mass of both particles was estimated to be about 5.27 GeV.

Phillip F. Schewe

1. S. Behrends *et al.*, Phys. Rev. Lett. **50**, 881 (1983).
2. Phys. Today **36**, 20 (April 1983).
3. Phys. Today **33**, 19 (October 1980).

Top Quark Search

The massive sample of data recorded at the CERN proton–antiproton collider in pursuit of the *W* particle may also harbor evidence for the top quark, some scientists believe.[1] In the CERN experiment, the handful of *W* particle events were those in which an electron (from the decay of the *W*) emerged with a large momentum transverse to the beam axis while the hadrons also produced in the collision had very little transverse momentum. Another class of events consisted of those in which a high-transverse-momentum electron was accompanied by an oppositely directed jet of hadrons. In certain reports, this type of event is interpreted as being perhaps the production of a pair of top quarks, each of which decays via the weak interaction into a bottom quark, an electron, and a neutrino.[2] The bottom quark would then decay and spawn a shower of lighter quarks seen in the detector as a jet of hadrons.

The hypothetical top quark fits very neatly into the "standard model" of particles and interactions (see *Physics News in 1981*, p. 46). It has been sought unsuccessfully for several years at the electron–positron colliders PEP (Stanford) and PETRA (Hamburg, West Germany). By applying the top-quark interpretation to the CERN electron-plus-jet events, a rough mass estimation for the top quark of 35 GeV has been calculated. A particle this heavy would be beyond the energy range of both PEP and PETRA.

It should be noted that explanations other than top-quark production have been advanced to account for these same events. Meanwhile, the UA1 and UA2 groups will be hunting through their mountain of data for evidence of the top quark and perhaps even other exotic particles, such as the Higgs boson.[4]

Phillip F. Schewe

1. Science **221**, 840 (26 August 1983).
2. V. Barger, A. D. Martin, and R. J. N. Phillips, Phys. Lett. B **25**, 343 (1983).
3. B. Adeva *et al.*, Phys. Rev. Lett. **50**, 799 (1983).
4. Nature **303**, 656 (23 June 1983).

Accelerator Building

From the time of E. O. Lawrence's desktop cyclotron of the 1930's to the present time, when the Fermilab synchrotron spreads across miles of Illinois prairie, accelerator energies have undergone a millionfold increase. How this tremendous energy is presently employed and how the worldwide map of accelerators will be changing in the coming decade are the subjects of this article.

Storage-ring accelerators employ two separate beams traveling in opposite directions around a circular track. These beams are smashed head on at one or more places around the track. The center-of-mass energy for such a collision is high, but the luminosity, the number of particles which are brought to bear on the collision region is low, owing to the relatively tenuous nature of each beam.

The other major accelerator scheme involves the collision of a beam of energetic particles against a fixed target, typically a chunk of metal. Since even a teaspoon of solid matter contains many more particles than even the most intense beam, the luminosity for a fixed-target accelerator is very high. Since the target particles are sitting at rest in the lab, though, the center-of-mass energy is low. Both of these factors are important: Center-of-mass energy determines what *kind* of reactions can take place, while the luminosity determines *how often* reactions will occur. In general, it is desirable to have high energy and high luminosity, although in practice one can seldom have both.

Most particle beams consist of protons or electrons. Other beams, such as positrons (antielectrons), antiprotons, mesons, neutrinos, and even photons are created by crashing electrons or protons into a stationary production target and selecting out the desired secondary particles from among the collision debris.

Electrons belong to the family of *leptons*, point-like particles which interact primarily via the electromagnetic force. The proton, in contrast, belongs to the *hadron* family and interacts primarily via the strong nuclear force. Because hadrons are composite objects, being made of quarks, the nuclear interaction between two hadrons can be very complicated. Indeed, the collision between a proton and antiproton has been compared to smashing two Swiss watches together.

If lepton collisions are so much "cleaner" than hadron collisions, why not use only lepton beams? Alas, as with the energy-versus-luminosity dilemma discussed above, the issue of lepton-versus-hadron beams involves tradeoffs. Electrons traveling around the circular arc of a storage ring continuously lose energy through synchrotron radiation at a rate proportional to the fourth power of the energy. The cost of counteracting this loss is a major factor in limiting the energy of circulating electron beams. Until now the principal lepton colliders PETRA and PEP (Stanford) have had a maximum beam energy of about 20 GeV. To produce particles as massive as the *W*, one usually needs the services of protons and antiprotons, which are more immune to the attrition of synchroton radiation and which can deliver the highest possible center-of-mass energy.

In general, no one can anticipate exactly the physics of tomorrow. Frequently the greatest discoveries occur in areas not included among the list of reasons for building the accelerator in the first place. On the other hand, some prognostications are superbly upheld. The electroweak theory, for example, prescribed a *W* particle with a mass of about 83 GeV. The CERN SPS synchrotron was adapted for proton–antiproton collisions and the *W* was duly found with a mass of 81 GeV.

This success and the expectation that, as in the past, new discoveries beckon in the energy range just over the horizon, have ensured that the bigger machines will get built, notwithstanding the constraints prevailing in government budgets. The following list of accelerator projects testifies to the strength and diversity of particle physics around the world.

CERN, Geneva, Switzerland. The scene of *W* and *Z* particle discoveries, CERN has long specialized in proton beams. Although there is a possibility that the p–$\bar{p}$ collider may be upgraded from 540 up to 900 GeV (by 1990), the primary construction effort will be LEP (Large Electron Positron storage ring), a 50- $\times$ 50-GeV e^+–e^- machine, 27 km in circumference, to be completed by 1988. A second phase will push the energy of each beam from 50 up to 130 GeV. At a luminosity of 3×10^{31} cm^{-2} sec^{-1}, LEP could produce about 10^8 *Z* particles a year. The Low Energy Antiproton Ring (LEAR) is a recently commissioned machine that stores antiprotons for specialized studies. For that purpose it siphons antiprotons away from the massive p–$\bar{p}$ collider.

Fermilab, near Chicago, Illinois. In the same tunnel, beneath the string of magnets constituting Fermilab's old synchrotron, a second string of magnets boost the energy of circulating protons the rest of the way up to 1000 GeV, or 1 TeV (1 trillion electron volts), hence the name TEVATRON. Besides delivering the highest beam energy in the world, this machine (at least the second stage of magnets) constitutes the world's first major superconducting accelerator. There are two principal TEVATRON construction phases: (i) the creation (by 1986) of beams of protons and antiprotons, each with an energy of 1 TeV to be collided head on, producing the world's largest center-of-mass energy, 2 TeV and (ii) the extraction from the machine of 1 TeV protons (by 1984) for use in fixed-target experiments. The Fermilab p–$\bar{p}$ collider should have a luminosity of about 10^{30} cm^{-2} sec^{-1}, about ten times larger than for CERN's p–$\bar{p}$ collider.

DESY (Deutsches Electronen Synchrotron) near Hamburg, West Germany. DESY is the home of PETRA, a 22- $\times$22-GeV e^+e^- collider. HERA is a machine (to be completed by 1990) in which 30-GeV electrons will collide head on with 800-GeV protons, producing deep inelastic interactions of tremendous force. The proton ring in this scheme might be superconducting.

SLAC (Stanford Linear Accelerator Center) at Stanford, California. Presently the home of PEP, an 18- $\times$ 18-GeV e^+e^- collider, SLAC will next bring forth SLC (Stanford Linear Collider), an accelerator scheme that will employ the existing linac to accelerate both electrons and positrons to energies of 50 GeV. The two beams emerge from the linac and are steered in opposite directions around a racetrack course and collide head on with an energy of 100 GeV, enough to produce the *Z* particle. SLC should be completed by 1986, in time to challenge the LEP machine at CERN. Since the beams are discarded after a single pass (unlike ordinary storage rings where circulating beams interact over and over again) the luminosity for SLC will be comparatively low.

BNL (Brookhaven National Laboratory) near New York City. The Colliding Beam Accelerator (formerly known as ISABELLE)

The tunnel of the main accelerator at Fermilab. The newly installed ring of superconducting magnets runs along the floor of the tunnel. These magnets will guide a beam of protons up to an energy of 1000 GeV. Directly above the superconducting ring is the older ring of conventional magnets. Various power and electronics cables run overhead.

was a proposed 400- $\times$400-GeV p–p collider with a high luminosity (10^{33} cm^{-2}sec^{-1}). The CBA project encountered early troubles in its ambitious superconducting magnet program and has been cancelled.[1] The 33-GeV proton synchrotron, the AGS, may be adapted to accelerate heavy ions.

Japan. At the KEK laboratory TRISTAN, a 3-km circumference 25- $\times$25-GeV e^+e^- collider should be finished by 1987. A more ambitious version of TRISTAN, employing electron–proton collisions at a center-of-mass energy of 200 GeV (by 1989), is being contemplated.

China. The 50-GeV Peking Proton Synchrotron, a project calculated to modernize in one leap the state of Chinese particle physics, has been cancelled. An electron–positron collider, called BEPC, will be built in its place (by 1987).[2]

USSR. Several gigantic projects loom in the Soviet future. At the Serpukhov Institute near Moscow, a 3-TeV proton accelerator is due by 1990. This machine, called UNK, might later (1993) accommodate p–$\bar{p}$ collisions at a total energy of 6 TeV. At the Institute for Nuclear Physics at Novosibirok a novel scheme has been devised: electrons and positrons will be fired at each other using opposing linacs, not storage rings. This complex, known as VLEPP, would at first use beams with an energy of 150 GeV, to be upgraded later to 500 GeV.

Future Accelerators. By 1990, accelerators will routinely be sending forth 50-GeV electrons and TeV protons. To move beyond that point will require either radically new accelerator techniques or—if conventional methods are to be used—the treasuries of many nations combined. The International Committee on Future Accelerators (ICFA) was formed to consider joint contributions toward the construction of a very big accelerator (VBA), a 10–20 TeV proton synchrotron, say. The European Committee for Future Accelerators (ECFA), not to be confused with the ICFA, has contemplated constructing just such a VBA in the LEP tunnel at CERN, perhaps sometime in the early 1990's.

On the western side of the Atlantic, the High Energy Physics Advisory Panel (HEPAP) makes recommendations to the U. S. Department of Energy as to where particle physics dollars can do the most good. At an important meeting held in the summer of 1983, HEPAP arrived at two major decisions.[3] The first was to abandon the CBA project at Brookhaven. The second was to recommend the building of a Superconducting Supercollider (SSC), a machine in which beams of 10–20 TeV protons would collide head on. The need to keep magnets simple and cheap would expand the overall size of the machine and necessitate the use of vast tracts of land (hence the nickname of "desertron").[4] The SSC project, costing perhaps a billion dollars or more and taking more than a decade to build, will soon begin its way through the Congressional review process.

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1. Phys. Today **36**, 17 (September 1983).
2. Sci. News **124**, 220 (1 October 1983).
3. Science **221**, 1038 (9 September 1983).
4. R. Diebold, Science **222**, 13 (7 October 1983).

Technicolor

There are four known fundamental forces in nature: gravity, electromagnetism, the weak nuclear force, and the strong nuclear force (also called the "color" force). When theorists succeeded in unifying the weak and electromagnetic forces, they solved a very important problem, but created a new one that has baffled theorists for several years. A possible resolution of the new problem requires that there be a fifth fundamental force, known as "technicolor." If the technicolor idea is correct, experiments to be carried out in Europe in 1987–88 will discover a new type of particle, called the "technipion," which is unlike any form of matter previously known.

The combining of the electromagnetic force with the weak force into a single unified interaction led to the 1979 Nobel Prize in Physics for Sheldon Glashow, Steven Weinberg, and Abdus Salam. In their electroweak theory, the two forces are unified in an almost symmetric way. This unification requires that there be new fundamental particles called "weak bosons," the W^+, W^-, and Z^0. These particles, recently discovered at CERN, are supposed to carry the weak force. Electromagnetism, on the other hand, is known to be carried by the photon, the basic particle of light. While the photon is exactly massless, the three weak bosons must be very heavy, roughly 90–100 times heavier than the proton. And it is this difference in the mass of the four particles that reflects the break in the symmetry of the unified electroweak force into its electromagnetic and weak components.

The important question this raises is: What is the basic interaction that brings about this symmetry breaking and the associated disparity in photon and weak boson masses? (The electroweak interaction itself cannot be the cause since it is known to be too weak.) In the original unification proposal, this question was left unanswered by the stratagem of introducing still another set of hypothetical fundamental particles, usually called "Higgs mesons." The Higgs mesons (see *Physics News in 1982*, p. 58) can couple to the weak bosons, giving them mass, but they do not couple to the photon which is left massless. What is so bothersome about this explanation is that it is based on arbitrary and *ad hoc* assumptions about the nature of Higgs mesons. That is, the theory did not have to work the way physicists wanted it to; the Higgs mesons could have left the weak bosons massless as well. All this arbitrariness is possible because the Higgs mesons were assumed to be fundamental particles.

This is where "technicolor" comes in. Technicolor is a new strong interaction proposed by Steven Weinberg and Leonard Susskind to explain why Higgs mesons should exist and behave as they do. If the technicolor interaction exists, Higgs mesons do not have to be elementary at all. Instead, they can be considered composite objects, made up of yet smaller particles called "techniquarks" which are held together by strong technicolor forces. All of this is analogous to the convention in which ordinary mesons are said to consist of ordinary quarks held together by the color force. The technicolor forces provide a natural explanation for the special way that Higgs mesons interact. Furthermore, the fact that techniquarks are roughly a thousand times heavier than ordinary quarks implies that a Higgs meson should weigh about 1000 proton masses.

The problem with all this—that a new force called technicolor causes new elementary particles called techniquarks to bind together to form Higgs mesons—is how to decide whether it is true. To do so, it would seem that physicists need particle accelerators capable of producing energies equivalent to at least 1000 proton masses. Some theorists have calculated that with the right sort of accelerator only one-tenth that energy may be needed. Specifically, they showed that techniquarks should bind together into particles other than just the Higgs mesons. These other particles are called "technipions" (technicolor analogs of pions) and there should be at least four of them, two that are electrically charged and two that are neutral.

Most important, the charged technipions should have a mass which is only 8 to 40 times the proton mass. Thus, the weak boson Z^0, 100 times heavier than the proton, will sometimes decay into a pair of charged technipions. So, the machine needed for testing the technicolor idea is one which can produce very large numbers of Z^0's—approximately 10 million per year!

At present, the only machine in the world that will be capable of producing so many Z^0's is LEP, the Large Electron Project, now under construction at CERN in Geneva, Switzerland. It should be completed by late 1987. The technipion search described here is already part of the approved experimental program at LEP. Thus, these experiments will be done in Europe, but not in the United States, because the U. S. does not plan to build the high-intensity "Z^0 factory" that is needed. While high-energy physics research must necessarily be a large, international enterprise, many U. S. physicists feel especially disappointed that these and other exciting experiments using the Z^0 will not be done here first.

Kenneth Lane, Ohio State University

FLUID DYNAMICS

Fluid dynamics is the study of the flow, compression, deformation, expansion, and viscosity of fluids (gases and liquids). Understanding the flow of fluids is important in the design of airplanes, ships, and engines; in predicting weather patterns; and in the search for new energy sources. Specific areas of research in the physics of fluids include the study of statistical mechanics, kinetic theory, the structure and general physics of gases, liquids, and other fluids, as well as certain basic aspects of fluid behavior as it pertains to such disciplines as geophysics, astrophysics, and biophysics. Examples include such topics as magnetofluid-dynamics, ionized fluid and plasma physics, shock wave phenomena, hypersonic physics, rarefied gases and upper-atmosphere phenomena, physical aeronomy, transport phenomena, hydrodynamics, boundary-layer and turbulence phenomena, liquid-state physics, and superfluidity.

Quantum Turbulence

Liquid helium at a temperature below 2.2°K behaves as if it consisted of two fluids: a normal viscous fluid and a superfluid. Consider a long channel filled with liquid helium and closed at one end. When the closed end is heated the superfluid fraction will flow toward the heater while the normal fluid will flow down the channel away from the heater. This extraordinary internal convection has been studied for about 40 years.

At low heats the motion of the two fluids just described is laminar; that is, the fluids flow smoothly through each other. But at higher heater power the superfluid is observed to be turbulent, and it is believed that this turbulence takes the form of a tangled mass of quantized vortex lines. A quantized vortex line in the superfluid is not unlike a bathtub vortex, except that the core of the vortex is of atomic size. The vortex lines can be of great length, and the tangle is not unlike the product of a cat and a ball of wool.

While there have been high hopes for the study of quantum turbulence, only recently has there been enough progress to cause excitement in the physics community. A recent review article outlines progress to about 1980.[1]

Quantized vortex lines can be detected by their property of absorbing a beam of "second sound." Second sound is a wave in which the normal and superfluid components oscillate back and forth. The quantized vortex lines can also be detected by their telltale ability to attract and capture negative ions in liquid helium.

Recent studies at the University of Oregon have shown that it is possible to construct a channel 1 cm × 1 cm × 40 cm in size, which has a constant vortex line density from the heater at the closed end down to the exit. Thus this small apparatus becomes a "wind tunnel" for quantum turbulence studies, and the turbulence is accurately homogeneous down the channel.

Simultaneous measurements of second sound and the temperature gradient along the channel have led the Oregon group to suspect that the vortex line density is quite flat in the axial direction; that is, the line density is greater looking across the channel than down it.[2]

Measurements with ions at IBM have shown that the vortex line density and the average normal fluid velocity are also homogeneous across the channel.[3]

Thus we arrive at the place where we have a well-characterized, compact source of quantum turbulence and can proceed to study the questions of important in turbulence. How are the vortices generated? How do they grow and decay to heat in the flow? What is the detailed nature of the vortex structures, their configuration, motion, interactions, and statistical properties?

A new and exciting era in turbulence research has begun.

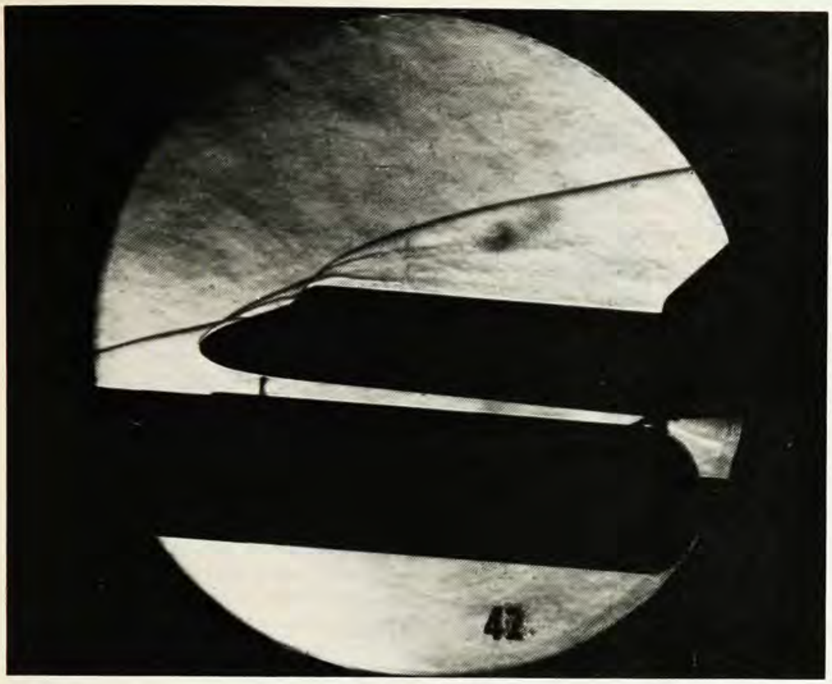
Russell J. Donnelly, University of Oregon

1. J. T. Tough, in *Progress in Low Temperature Physics*, edited by D. F. Brewer (North–Holland, Amsterdam, 1982), Vol. VIII.
2. C. F. Barenghi, C. E. Swanson, and R. J. Donnely, in 75th *Jubilee Conference on Helium*-4, edited by J. G. M. Aritage (World Scientific, Singapore) (in press).
3. F. P. Milliden and K. W. Schwarz, Bull. Am. Phys. Soc. **28**, 254 (1983).

The Ranque–Hilsch Effect

Researchers at the University of Tennessee Space Institute have emerged with a radical explanation of the Ranque–Hilsch effect, a spectacular and mysterious separation of air in swirling motion into hot and cold streams, and have traced the cause to a whistling sound present in the vortex flow.

In 1933, Georges Ranque, a French engineer, uncovered a striking phenomenon: when compressed air was introduced into a pipe through tangential injection holes (imparting a swirling motion) the temperature near the tube centerline became freezingly cold, while the temperature near the tube periphery exceeded its inlet value. This temperature separation took place without the aid of any external mechanical device. The effect became popularized later through a paper by Rudolf Hilsch, a German scientist. The device which became known as the Ranque–Hilsch tube or vortex tube is now commercially available; it is routinely used as a refrig-



This photograph shows the shock-wave pattern that occurs on the Space Shuttle Orbiter and External Tank during their ascent flight at a Mach number of 8. Note that the bow shock wave from the nose of the External Tank impinges on the nose of the Orbiter, creating a complex pattern of shock waves and vortex sheets. This complex flow phenomena significantly alters the local heat transfer to the nose and windshield of the Orbiter. The photograph was taken in the Hypersonic Shock Tunnel at Calspan Corporation in Buffalo, New York.

erator without a motor or other moving parts for such purposes as machining operations and protection of electrical equipment, since even with inlet air at room temperature and at readily attainable pressure of a few atmospheres, cold air below 0°F can easily be obtained.

In spite of the simplicity of the Ranque–Hilsch tube, the mechanism of temperature separation has been a matter of long-standing dispute. Despite many attempts, the process eluded an adequate explanation; some attributed this, in a lighter vein, to Maxwell's demon, an imaginary being invented in the nineteenth century by James Clerk Maxwell. This microscopic demon would divide up the air by storing faster-moving molecules in one compartment and slower-moving molecules in another.

It had now long been recognized that a high-intensity whistling sound—the so called vortex whistle—emanates from vortex flow in general and from the Ranque–Hilsch tube in particular. Although previously regarded merely as an annoying by-product of such swirling flows and nothing more, the Tennessee scientists hypothesized that this vortex whistle was, in fact, the main cause of the Ranque–Hilsch effect.[1]

In order to verify this, they installed acoustic suppressors, specially designed and tuned to the frequency of the vortex whistle, on a Ranque–Hilsch tube. When the pitch of the vortex whistle, which increases as the flow through the tube is increased, hit the tuned frequency, the sound level suddenly tumbled by 25 dB, changing from an ear-splitting whistle to a muffled hiss. At that very instant, the tube centerline temperature, which had gone down to as low as −32°F, immediately leapt upwards to +33°F (a temperature jump of 65°F), while the temperature near the tube periphery plummeted by 10°F. This supported the theory that the vortex whistle was indeed the main cause of the Ranque–Hilsch effect.

The sound deforms the distribution of swirl velocity in the radial direction through the mechanism of acoustic streaming. Acoustic streaming, or sonic wind, is in general a phenomenon in which sound or alternating currents of flow modify the time-averaged, or direct, currents of flow; it is, in a sense, analogous to the more familiar generation of electric heat by alternating current. Owing to this acoustic streaming induced by the vortex whistle, the flow becomes distorted in such a pattern that the swirl velocity, with a zero velocity near the centerline, continues to increase in the radial direction, like the rotation of a car tire. When the air eventually comes to rest, the higher velocity near the periphery is converted into warmer temperature while the lower velocity near the centerline is converted into colder temperature.

M. Kurosaka, University of Tennessee

1. M. Kurosaka, J. Fluid Mech. **124**, 139 (November 1982).

MEDICAL AND BIOLOGICAL PHYSICS

The instrumentation and laboratory techniques used in physics research have been employed in the study of medicine and biology for many years. X rays, ultraviolet radiation, and high-energy charged particles have been used in medical diagnosis and therapy for some time. The continual evolution of lasers, specialized particle accelerators, sophisticated detectors, and computer analysis adds to the stock of medical tools.

Of particular importance are devices which can render images of the body's internal structure and the chemical processes at work there. These include computer tomography (using x rays), emission tomography (using positrons), nuclear-magnetic resonance, and ultrasonics.

The articles which follow pertain to a wide variety of subjects in medical and biological physics research: the development of guidelines for use of nuclear-magnetic-resonance imaging, hyperthermia, radiation therapy planning, ultrasound tomography, sensory thresholds, and the skin's ability to locate touch sensations.

Nuclear Magnetic Resonance: Usage Guidelines

Nuclear magnetic resonance (NMR) has emerged over the past ten years as a commercially available technique for diagnostic imaging. NMR conveys information about physiology and body chemistry. This is in comparison to the information about anatomy and organ function presently available from other diagnostic imaging techniques. The addition of NMR to the diagnostic imaging field further expands the techniques available and the information available for diagnosis. It is also of interest since, as with ultrasound, it does not rely on ionizing radiation and does not expose the patient to a dose of radiation.

The basis of NMR rests on the fact that most chemical elements have at least one isotope whose nucleus is magnetic.[1,2] Such a nucleus, when placed in a magnetic field, can assume a low-energy state by aligning with the field or a high-energy state by aligning against the field. If a weak, rapidly alternating magnetic field is applied near a patient, changes in the orientation of the nucleus will occur. This process results in the absorption of energy and the subsequent emission of electromagnetic radiation at a resonance frequency. Different elements and different isotopes have different response frequencies. NMR, through the use of spectroscopic techniques, identifies the frequencies and provides information on molecular structure and identity within the patient. Present machines operate with magnetic fields in the range of 500 to 5000 G.

The study of the biological effects of high magnetic fields is an expanding area.[3] There are presently no standards for human exposure to magnetic fields, but guidelines for allowable occupational exposure levels have been suggested by two laboratories. The Fermi National Accelerator Laboratory sets the ceiling at 10 kG for short exposures and 100–5000 G for long exposures. The Stanford Linear Accelerator Center Laboratory sets ceilings for short- and long-term exposures at 2 kG and 200 G, respectively.

One NMR manufacturer has warned[4] that static fields of even 5 G or greater may present a health hazard to persons wearing cardiac pacemakers; in the vicinity of a 1.5-kG machine the perimeter at which the field was at a 5-G level would be between 15 and 18 ft; for a 5-kG machine, it would be between 31 and 38 ft. It is expected that more definitive advice will be forthcoming from such professional organizations as the American Association of Physicists in Medicine, and from regulatory limits issued by governmental agencies.

George Holeman, Yale University, Dept. of Health Physics

1. G. L. Brownell, T. F. Budinger, P. C. Lauterbur, and P. L. McGeer, Science **215**, 619 (1982).
2. Ian Pykett, Sci. Am. **246**, 78 (May 1978).
3. J. H. Battocletti, S. Salles-Cunha, R. E. Halbach, J. Nelson, A. Sances, Jr., and F. J. Antonich, Med. Phys. **8**, 115 (1981).
4. Picker International, "Site Planning Guide NMR Resistive and Superconducting Systems."

Hyperthermia

In the late 19th century it was observed that cancer patients who suffered severe infections with accompanying high fevers occasionally displayed partial or complete regression of their tumors. It was speculated that the regressions resulted from either the stimulation of the immune systems by the infections, or the direct effect on the cancer cells of the hyperthermia associated with the fever, or both. Subsequent to these observations, clinical studies employing systematic hyperthermia to treat cancer were conducted, in which the "fever" was induced artificially through injection of patients with bacterial toxins (pyrogens) or placement of patients in heated chambers. By the mid 1930's, however, the use of the systemic hyperthermia as a therapeutic cancer modality had all but ceased, in part no doubt because of the disappointing results obtained with the procedure, but also because of the emergence of other powerful anticancer modalities, particularly radiotherapy.

During the past decade a renewed interest in hyperthermia has surfaced, and activity related to the use of heat to treat human malignancies has grown very rapidly. During this period, laboratory studies with cells and animals have shown that temperatures elevated above 42.5°C (108.5°F) for a sufficient period of time (e.g., 30–60 min) can kill cells outright and can also enhance the ability of ionizing radiation to kill cells.[1] Most important, it has been convincingly demonstrated that both the direct cytotoxic action of heat and heat-induced radiosensitization are generally more pronounced for cells in malignant tissues than for cells in adjacent normal tissues.[1] Provided with a sound basis by the variety of biological and physiological studies alluded to above, hyperthermia is currently being employed clinically in a number of institutions in the United States, Canada, Europe, and Japan. Although systemic hyperthermia (induced with physical agents, not pyrogens) is being administered at a few centers worldwide, at present clinical hyperthermia is employed predominantly to heat local and regional tissue sites. Typically, a full course of clinical hyperthermia will contain from three to ten treatments (30–60 min each), administered at the rate of two to three treatments per week. The results obtained to date indicate that hyperthermia, employed in combination with radiotherapy, for example, can effect rapid and substantial tumor regression with relatively modest effect on normal tissue.

The heating of tissue required in clinical applications of local and regional hyperthermia is produced through the deposition of power *in vivo* by physical agents such as electromagnetic radiation at very high- and microwave frequencies, electric fields at radiofrequencies, and ultrasound at frequencies from 0.3 to 3.0 MHz.[2] For local hyperthermia produced with externally applied microwaves (from waveguide applicators) frequencies between 300 and 2450 MHz typically are used, permitting extension of therapeutic tissue heating to depths of 3–4 cm. At much lower frequencies, such as 50–100 MHz, electromagnetic radiation can heat tissue therapeutically to depths of up to 15 cm, permitting tumors at the very center of the body to be treated.

Hyperthermia at these frequencies is necessarily regional, however, because of the large applicator aperture sizes required, and the deposition of substantial amounts of power at all depths between body surface and center. Localized, therapeutic tissue heating to depths of up to 6 cm can be produced with a single beam of externally applied ultrasound. Furthermore, a number of ultrasound transducers can be positioned to define a "multiple beam" array that, in contrast to electromagnetic agents, can produce localized heating at depths of up to 15 cm. However, ultrasound cannot penetrate even small thicknesses of bone and is nearly totally reflected at all tissue–air interfaces. Hence, the anatomic sites and tissue regions to which ultrasound-induced hyperthermia can be applied are necessarily limited.

At present, clinical thermometry—that is, measurement of temperature distributions produced in applications of clinical hyperthermia—is performed virtually exclusive with invasive temperature probes. Until recently, only conducting probes with metallic leads were available for use. When employed to measure temperature in applications of microwave and radio frequency-induced hyperthermia, probes of this type—such as standard thermistors and thermocouples in 20- to 29-gauge hypodermic needles and plastic tubes—can couple directly to the electromagnetic field, leading to direct probe heating and noise in probe readout circuitry. Errors in temperatures determined under such conditions can be substantial.

During the last few years, however, temperature probes have been developed that are effectively transparent to electromagneic fields. Thermometers such as high-resistivity thermistor probes with carbon impregnated plastic leads (in 16-gauge tubes) and thoroughly non-conducting "optical" probes (in 16- to 20-gauge lumens) are now employed routinely for thermometry in clinical hyperthermia. The optical probes consist of specific optical sensors and optical fibers. Non-invasive thermometry has been and continues to be the subject of considerable research, as its advantages over thermometry with invasive probes are obvious. Techniques employed or under investigation include infrared thermography, microwave thermography (radiometry), and ultrasound reconstruction. However, except for infrared thermography, which is commercially available but which yields information on surface temperatures only, a non-invasive thermometer well suited to the needs of clinical hyperthermia does not now exist.

Given the solid rational for hyperthermia and the encouraging clinical observations to date, the future of thermotherapy as an anticancer modality would appear to be bright. However, the satisfactory development of clinical hyperthermia as a safe, effective, and quantitative method of treating malignant diseases will ultimately depend on the extent to which the physics and physiology of local, regional, and whole-body heating of human tissue are understood and incorporated into the planning and administration of thermotherapy. Whatever its promise, the value of hyperthermia as a clinical tool will be governed and perhaps limited by the physical aspects of power deposition, heat transfer, and thermometry *in vivo*.

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1. George M. Hahn, *Hyperthermia and Cancer* (Plenum, New York, 1982).
2. *Physical Aspects of Hyperthermia*, edited by Gilbert H. Nussbaum (American Institute of Physics, New York, 1982), AAPM Monograph No. 8.

Radiation Therapy Treatment Planning and Delivery

Modern day radiation therapy practice, with emphasis on precision high-dose radiation treatments, demands careful treatment planning and delivery. With the availability of more sophisticated imaging technology and a new generation of compact medical linear accelerators, the use of high-energy proton and electron beams as a primary modality for the treatment of cancer is being further expanded. The successful outcome of a radiation treatment program necessarily rests on the accuracy in which each step of the process is carried out. Thus, accurate knowledge of the radiation dose delivered within the irradiated volume is an essential element in the treatment process.[1,2]

Diagnostic imaging equipment has been significantly improved in the past decade and now provide good three-dimensional information about an individual patient's anatomy and tumor extent. Computed tomography (CT) has had the largest impact in this area and nuclear magnetic resonance (NMR) may play a prominent role in the near future. A complete three-dimensional representation of the patient can be synthesized using data from these modalities combined with the information from the radiation theory x-ray simulator and nuclear medicine studies.

Although computers are now in widespread use in radiation therapy,[3,4] they are usually applied to only a narrow component of the overall task of planning and executing radiation therapy, namely the calculation of the dose distribution. However, generally the calculation of dose is performed under restricted conditions, namely in one, or sometimes a few, two-dimensional planes for idealized irradiation conditions.

All of these developments now make it possible to consider the application of computer, accelerator, and imaging technologies to a much broader range of problems in radiation therapy. Imaging devices include CT scanners, NMR imaging (which promises both to rival and complement CT), emission computed tomography, and several other digital imaging techniques. Modern linear accelerators with microprocessor-control delivery systems have proven useful in delivering radiation treatments. Gantry-mounted units with high-energy photon and electron capabilities are replacing the standard cobalt-60 units. Shielding blocks and tissue compensators fabricated individually for each patient are used extensively for shaping the radiation treatment fields and ensuring uniform dose distribution. Multifield treatment techniques and moving beam therapy for optimizing dose distributions are widely used.

New techniques are being developed to assist the treatment planner in decisions about the choice of beam orientation and the sizes and shapes of the radiation fields.[5,6] Chief among these is a "beam's eye view" display in which the observer's eye is hypothetically placed at the radiation source looking out toward the patient along the central beam axis. When the computation is made fast enough that the viewpoint can be altered interactively, this presentation is an excellent way of perceiving the important anatomical relationships and, is ideal for defining the field size and shape.

The lack of anatomical and tissue density information limited early attempts to achieve accurate dose calculations. Now, CT provides the necessary data, and thus dose calculations based on individual CT pixel information make improved accuracy possible.[7,8]

Recently developed compact waveguides have made possible the construction of specialized treatment machines with dual photon energy capabilities. Another promising development is the "microtron" with its ability to transport several beams from a remote site to the treatment rooms.[9] Significant research has been undertaken to improve the photon and electron beam physical characteristics from current treatment machines. Improved photon depth doses (through better target and flattening filter design) and improved electron beam depth doses (through the use of scanning electron beams or shaped multiple scattering foils) have been accomplished.[10,11]

Another area showing considerable promise is in computer-controlled radiation treatment delivery,[12,13] where photon dose distributions superior to those obtained using conventional therapy equipment can be made. The advantage of this technique derives from its ability to shape dose distributions in three dimensions. Certain parameters of the therapy machines, such as gantry angle, collimator position, treatment table position, and dose rate are continuously adjusted during the treatment times to deliver a maximum dose to the tumor-bearing volume while keeping the dose to normal tissues below specified values.

James Purdy, Washington University School of Medicine

1. J. G. Stewart, A. W. Jackson, Laryngoscope **85**, 1107 (1975).
2. R. Morrison, Clin. Radio. **26**, 67 (1975).
3. "Computers in Radiation Therapy," in *Proceedings of the Seventh International Conference on the Use of Computers in Radiation Therapy, Tokyo, Japan, 1980.*
4. L. Cohen, in *Proceedings of the Sixth International Conference on the Use of Computers in Radiation Therapy—Gottingen, 1977*, pp. 25–32.
5. D. McShan *et al.*, Br. J. Radiol. Suppl. **15**, 144 (1979).
6. M. Goitein *et al.*, in *Computed Tomography in Radiation Therapy*, edited by Ling *et al.* (1983), pp. 175–176.
7. M. R. Sontag and J. R. Cunningham, Radiology **129**, 787 (1978).
8. J. W. Wong and R. M. Henkelman, Med. Phys. **10**, 199 (1983).
9. A. Brahme, Ph.D. thesis, University of Stockholm, 1975.
10. N. K. Sherman *et al.*, Med. Phys. **1**, 185 (1976).
11. P. R. Almond, in *Proceedings of the Symposium on Electron Beam Therapy, New York, 1979*, pp. 45.53.
12. P. K. Kijewski and B. E. Bjarngard, in *Computers in Radiation Therapy* pp. 277–282.
13. L. M. Chin, P. K. Kijewski *et al.*, Int. J. Radiat. Oncol. Biol. Phys. 7, 61 (1981).

Ultrasound Tomography

A recent mathematical advance may help to bring computer-aided tomography, popularly known as CAT scanning, out of large hospitals and research centers and into the doctor's office for routine preventive health care. Work done at Schlumberger–Doll Research in Ridgefield, Connecticut, may lead to the production of clear images of the human body with tomography based not on x rays, as in present commercial scanners, but on ultrasound—high-frequency sound waves inaudible to humans.[1] This has been a major research goal in medical imaging over the past few years, because it could lead to the development of cheaper, safer CAT scanners.

Since its invention in the late 1960's, computer-aided tomography has revolutionized medical diagnosis by providing startlingly clear images of the internal organs and fleshy tissue in cross sections of the human body. Today's commercial scanners produce these images by passing a beam of x rays through the patient in many different directions and then combining the different x-ray shadows into a single picture by a mathematical algorithm, which was first derived by the Austrian mathematician Radon in the early 1900's but which was only refined and adapted to medical imaging in the 1970's.[2]

X-ray tomographic scanners do have drawbacks, however. Since they must generate and control x rays, which are very-high-frequency light waves, commercial scanners are both cumbersome and expensive. But even more important, doctors have been reluctant to request CAT scans routinely because of the side effects that can follow exposure to repeated doses of radiation. These drawbacks led scientists, principally at the Mayo clinic, to investigate whether ultrasound could replace x rays in the tomographic process.[3] In many respects, ultrasound waves are ideal for this purpose. Not only are ultrasound waves relatively easy and inexpensive to generate, but they also seem to induce few side effects in healthy human tissue.

Researchers soon found, however, that the images produced by ultrasound scans were much more difficult to read than x-ray CAT scans. The reason is that unlike x rays, which nearly always travel in straight lines, ultrasound waves are easily deflected from their initial straight paths in passing through the body. This scattering or diffraction of the ultrasound tends to defocus the original beam and consequently to blur the final image. It is here that the research at Schlumberger–Doll may provide the key breakthrough. Based on principles of optical imaging, the work showed how the scattered ultrasound wave can be refocused into crystal clear images by a suitable modification of the mathematical algorithm that processes x-ray images. The new algorithm has been named filtered *backpropagation*, in analogy to the name filtered *backprojection*, which has been given to the simpler algorithm of x-ray tomography.[4]

The algorithm of x-ray tomography has been compared with the filtered backpropagation algorithm in computer simulations of ultrasound tomography.[1,5] These simulations indicate that the x-ray algorithm, when used for ultrasound tomography, produces blurred images, a result that is in agreement with experimental observations made at the Mayo clinic.[6] On the other hand, the filtered backpropagation algorithm produced excellent reconstructions in all of the computed examples. In fact, it was found that the images obtained from ultrasound scans when processed by the new algorithm can be superior to similar images obtained from conventional x-ray scans. This surprising result can be traced back to a focusing effect which is present in the formation of the ultrasound image by the filtered backpropagation algorithm, but which is absent in the image formation process for x-ray imaging systems.

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1. A. J. Devaney, paper D-3 presented at the Meeting of the Acoustical Society of America, J. Acoust. Soc. Am. Suppl. 1 **73**, S9 (1983).
2. G. N. V. Ramachandran and A. V. Lakshminarayanan, Proc. Natl. Acad. Sci., U. S. A. **68**, 2236 (1971).
3. J. F. Greenleaf, S. A. Johnson, S. L. Lee, G. T. Herman, and E. H. Wood contribution in *Acoustical Holography*, edited by P. S. Green (Plenum, New York, 1974), Vol. 5, pp. 591–603.
4. A. J. Devaney, Ultrason. Imag. **4**, 336 (1982).
5. A. J. Devaney, IEEE Trans. Biomed. Eng., **BME-30**, 377 (1983).
6. J. F. Greenleaf and R. C. Bahn, IEEE Trans. Biomed. Eng., **BME-28**, 177 (1981).

Sensory Thresholds

The world is a noisy place. Discerning small signals amid a bustling climate of motion, friction, and turbulence is often a matter of survival for plants and animals, and a number of complex sensing systems have evolved for this purpose, systems that operate as well as—and in some cases, better than—the most advanced electronic detectors. The human eye, for example, can detect single photons. The ear can detect sounds that displace the fluids around the stereocilia, the finger-like appendages to the inner-ear hair cells, by less than a billionth of an inch, ten times smaller than a single atom. William Bialek of the University of California at Berkeley is attempting to account for such exquisitively fine sensory behavior using quantum mechanics.[1]

Even when gross external noise can be eliminated, the reception of weak signals is still hindered by thermal noise, the noise associated with the inherently chaotic motion of the atoms in the receptor (at any temperature greater than absolute zero), and quantum noise, which corresponds to the uncertainty in the position and motion of atoms as determined by quantum mechanics. At room temperature a comparison of thermal to quantum noise is equivalent to comparing the sound of a jet engine to a whisper. That is, quantum noise is usually negligible.

When Bialek calculated what the thermal noise of the sterocilium should be, he found that it corresponded to displacements 100 times larger than those associated with signals to which the hair cells responded. These signals, by the way, carry a power of about one-billionth-billionth watt, the power carried by a signal from a Voyager spacecraft.

Bialek recalculated the thermal noise using a model in which the sterocilia are not considered as passive, rigid rods, but rather as miniature muscles which actively respond to the signal. Different stereocilia might be "tuned" to respond to and amplify special sound frequencies while ignoring all others, such as those which constitute broadband thermal noise. This tuning hypothesis seems to work well. One consequence of the theory is that the stereocilia might move (or "beat") spontaneously without an acoustic input, thus generating a sound of their own. Such acoustic emissions have been observed in man and animals.[2]

Having thus surmounted the problem of thermal noise, the sound receptors in the ear appear to be operating near the threshold of sensitivity allowed by quantum noise. This leads to the interesting conclusion that the reception of sound, and other sensory phenomena as well, must be treated with the rigor of quantum mechanics.

Phillip Schewe

1. William Bialek, presented at the March Meeting of the American Physical Society, Los Angeles, California, 21–25 March 1983, paper EC-4.
2. Sci. Am. **244**, 96 (May 1981).

The Mutability of Time and Space on the Skin

Man's senses differ widely in their ability to perceive the dimensions of time and space. It is the distortion of these dimensions that gives rise to the most dramatic and disturbing illusions in our experience. With a rise of body temperatures above 38°C, for example, we commonly experience a severe distortion of time: minutes may seem like hours. If we gaze at a single point of light in the dark we may see it move in elaborate spatial patterns when in fact it is stationary.

Fortunately, such disturbances do not involve all the senses at once, nor do the various senses represent time and space to us with equal effectiveness. The chemical senses of smell and taste can hardly be said to represent space at all; their main function is to tell us about the myriad qualities in our food and drink, and in the air we breathe. The ear is the superior sense for time discrimination and representation, but falls clearly behind the eye as a spatial sense. The eye, on the other hand, is the spatial organizer without peer, but behaves sluggishly in the temporal domain. Lying between the ear and the eye is the sense of touch, which organizes space better than the ear, and time better than the eye.

The skin's capacity for locating touches is considered limited, as is known by anyone who, blindfolded, has played the game of trying to reproduce the touch of a pencil point delivered to the skin by another person. There is a normal "error of localization," large in some parts of the body such as the back, but fairly small in the more sensitive regions (lips and fingertips). Such errors are relatively inconsequential compared to those that have been under study for the past decade in the Cutaneous Communication Laboratory of Princeton University. With the right timing of stimuli, mislocalizations far exceeding the normal error of localization can be induced. If very brief contact is made with the skin of the forearm, lasting only a few thousands of a second, say, and a short time afterwards the arm is similarly touched 5 in. away, the first touch will not be felt where it "really" occurs but will be displaced somewhat towards the second spot. If the time between pulses is as much as one-quarter of a second, the displacement will be very small, perhaps imperceptible, but if the time is somewhat less, say one-tenth of a second, the first tap will seem to have traveled about halfway toward the second one. If the time is now halved to fifty-thousands of a second, three-quarters of the distance will have been eaten up, and if only twenty-thousandths of a second separate the two pulses the first tap will fall on top of the second one, and only a single strong tap will be felt.

By suitable experiments it can be demonstrated that this instability of touch sensation is primarily the result of something special happening at the brain level, not "out there" in the skin. It seems that the brain can hold a touch impression for about one-quarter of a second. If nothing happens in the neighborhood to modify it, the impression stabilizes and the touch that generated it is felt, within the normal error, where it "is." If a second pulse occurs nearby within that interval, the first impression is drawn towards the second. Just how far the second tap appears to be displaced depends mainly on the time interval between the two. The distance is short if the time is long, but long if the time is short.

This jumping out of place has been called by the Princeton investigators "saltation" (from the Latin, *saltare*, to leap, jump, or dance). In addition to demonstrating that the leaping distance depends on time, they have shown that there is a circumscribed area of skin, different in size from one part of the body to another, within which the displacements will occur. The "saltatory area," as they call it, is quite large on the thigh, chest, and arm, smaller on the palm of the hand, and tiny on the fingertip. This tells us a good deal about how the cortex of the brain is organized to receive tactile impressions, for the saltatory areas prove to be related in a predictable way to the size of corresponding brain areas.

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NUCLEAR PHYSICS

Nuclear physics is the study of the properties of the atomic nucleus. The atom can be described in terms of various electron quantum energy states. These states differ in energy by a few electron volts. The atomic nucleus, in some models, can also be described in terms of energy level states for the constituent nucleons. These levels differ by thousands or millions of electron volts. The shape of the nucleus, the disposition of nucleons inside, and the interactions between nucleons can be studied by observing radioactive decays, and by scattering beams of high-energy particles from nuclear targets. The advent of particle beams of higher energy and greater intensity, the use of polarized beams and targets, the use of heavy ion beams, and the use of more complex particle detectors are opening up new areas of nuclear physics research.

The Production of Heavy Elements

Nuclei are made out of protons and neutrons. The stability of this mixture is restricted three ways. If nuclei have too many neutrons, neutrons "drip out." If they have too many protons, protons are lost. And if the electrostatic forces in nuclei overcome the nuclear forces, they fission. Three borderlines surround the land of nuclear stability: the neutron dripline, the proton dripline, and the fission barrier.

New nuclei are produced by fusion reactions, in which an accelerated projectile nucleus amalgamates with a stationary target nucleus. Recent experiments at the UNILAC accelerator[1] in Darmstadt, West Germany, have created nuclei up to the borderlines of stability. A key to the search and identification of the short-lived nuclei was the specially designed detector apparatus, called the Separator for Heavy Ion Reaction Products.[2,3] The newly created nuclei emerge from the target with a high velocity and enter the SHIP apparatus.

The recoil velocity is determined by SHIP, which acts as a velocity filter allowing the heavier amalgamated fusion products to separate from all other nuclei involved in their production. After separation by SHIP, the fused systems crash into silicon surface barrier detectors; the time and the locus of implantation, and the energy of the implanted product can then be determined. As the fusion product is imbedded into an active detector as a well-defined spot, all its subsequent radioactive decays can be registered by the same detector with a very high efficiency. The analysis of all signals registered from one event allows identification of single radioactive nuclei.

UNILAC-SHIP and its detector system are a unique combination of instruments developed during the period 1972–1978 by a group of physicists from GSI Darmstadt and University of Giessen, allowing the production, separation, and detection of radioactive isotopes produced via fusion with a previously unknown sensitivity. Five landmarks in the exploration of nuclear stability were achieved:

(1) Two new elements have been created, with proton numbers 107 and 109. In order to produce elements beyond the highest Berkeley-made element 106,[4] which had been made with more than 40 MeV of excitation energy, fusion processes leading to less excitation had to be investigated. More symmetric and strongly bound "magic" nuclei as collision partners allow fusion with excitation energies between 15 and 20 MeV. Following experiments by Dubna scientists who used lead and bismuth targets to make heavy elements,[5] the GSI scientists produced isotopes of elements fermium, mendelevium, nobelium, 104, 105, 107, and 109.[6,7] Seven nuclei of element 107 and one nucleus of element 109 have been identified. The GSI claim to have discovered elements 107 and 109 rests on these few nuclei.

(2) The proton dripline, one of the borderlines of nuclear stability, has been reached and crossed. The nuclei lutetium-151 and thulium-147 are proton radioactive.[8,9]

(3) At the triple point of equal stability against fission, proton, and neutron emission, the nucleus mercury-180 has been produced via the fusion of two shell stabilized zirconium-90 nuclei.[10] It was shown that the nucleus deexcited by gamma emission only. The radiative capture of the two heavy nuclei has been established unambiguously by SHIP. It is the "coldest" fusion reaction ever made.

(4) The question of whether two nuclei fuse or not depends on the ratio of the disruptive electrostatic forces and the attractive nuclear forces between the two amalgamating nuclei. The limit of fusibility has been established at a ratio of about 0.8 for the two forces. Beyond this limit, fusion is only possible by adding more

translational energy to the colliding nuclei. This "extra-push" energy leads to fused systems of higher intrinsic energy or temperature. Cold fusion and the production of fission-limited nuclei become impossible.

(5) All known elements beyond uranium have nuclei which are spheroidally deformed and shell stabilized. The shell stabilization is active up to 40 MeV of excitation energy. The spherical nuclei near the closed neutron shell 126 are shell stabilized as well, but it was shown that a spherical nucleus could lose its predominant spherical shell stabilized shape already at 15 MeV of excitation energy. The production of superheavy elements stabilized by the 184 closed-neutron shell was simulated by fusion studies of nuclei with 126 neutrons.[11] The studies showed superheavy elements must be produced with excitation energies smaller than 20 MeV.

This progress encouraged a new attempt to produce superheavy elements. In a GSI collaboration with Lawrence Berkeley Laboratory, several experiments have been performed using calcium-48 bombardments of manmade curium-248 targets in an attempt to produce the superheavy elements $Z = 116$. Excitation energies between 15–20 MeV and a range of half-lives between 10^{-6} and 10^{6} sec have been covered in a recent experiment at SHIP. Cross section limits of 5–10^{-35} cm^2 have been reached. The data evaluation is still in progress.

A possible production of superheavy elements depends on the extrapolations made for the presence of cooling mechanisms, the "extra-push" energy, and the temperature dependence of shell effects in spherical nuclei. If superheavy elements cannot be made with small intrinsic excitation energy, they will not be made.

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1. N. Angert and Ch. Schmelzer, Kerntechnik **9**, 57 (1977).
2. G. Münzenberg, W. Faust, S. Hofmann, P. Armbruster, K. Guttner, and H. Ewald, Nucl. Instrum. Methods **161**, 65 (1979).
3. S. Hofmann *et al.*, Conference on Nuclei Far from Stability, Helsingør, Denmark, 1981, CERN Report No. 81-09, p. 190.
4. A. Ghiorso, Proceedings of the International Conference on Actinides '81, 23 (1982).
5. Yu. Ts. Oganessian, A. S. Iljinov, A. G. Demin, and S. P. Tretyakova, Nucl. Phys. A **239**, 353 (1975); Yu. Ts. *et al.* Nucl. Phys. A **273**, 305 (1976).
6. G. Münzenberg *et al.*, Z. Phys. A **300**, 107 (1981).
7. G. Münzenberg *et al.*, Z. Phys. A **309**, 89 (1982).
8. S. Hofmann, W. Reisdorf, G. Münzenberg, F. P. Hessberger, J. R. H. Schneider, and P. Armbruster, Z. Phys. A **305**, 111 (1982).
9. O. Klepper, T. Batsch, S. Hofmann, R. Kirchner, W. Kurcewicz, W. Reisdorf, E. Roeckl, D. Schardt, and G. Nyman, Z. Phys. A **305**, 125 (1982).
10. J. G. Keller *et al.*, Z. Phys. (to be published).
11. K.-H, Schmidt *et al.*, *Proceedings of the International Symposium on Physics and Chemistry of Fission*, Jülich (IAEA Vienna, 1980), Vol. I, p. 409.

New Giant Resonances

There is considerable interest in simple modes of excitation of the nucleus called giant resonances. These excitation modes correspond to the coherent motion of a large fraction of the nuclear constituents, the neutrons and protons.[1] Oscillation modes similar to those of a liquid drop have been most extensively studied by experiment. Other oscillation modes involving the intrinsic spin possessed by nucleons have not been as extensively explored.

The most famous example of a spin-independent nuclear oscillation is the giant dipole resonance. This resonance is one of the simplest oscillatory modes: the neutrons of the nucleus move in one direction while the protons move in the opposite direction, thereby creating a net electric dipole moment. The other examples of giant resonances (monopole, quadrupole, and octupole) involve motions in which neutrons and protons move together.

The fact that nucleons are endowed with an intrinsic spin which can point in only one of two directions makes possible other dipole modes of oscillation of the nucleus. One such mode occurs when nucleons with their spin vectors pointing up oscillate out of phase with nucleons whose spins point down. Another mode occurs when neutrons with spin up and protons with spin down oscillate against neutrons with spin down and protons with spin up. These modes have been hypothesized by theorists for many years[2] but had not been observed in experiments. Their properties would yield a great deal of information about the spin-dependent forces that help hold the nucleus together.

Most of the new information on giant resonances has come not from electron scattering, but from inelastic scattering of hadrons (such as protons or pions) from the nuclei. In particular, the spin and isospin (the latter having to do with the relative phase of the motions of neutrons and protons) degrees of freedom can be selectively excited by a suitable choice of reaction. For example, proton scattering at small angles was used to find the magnetic dipole resonance in heavy nuclei.[3] The M1 (magnetic dipole) state has been well known in light nuclei for many years. Until recently, however, the absence of substantial M1 strength in nuclei beyond $A = 60$ was a major mystery in nuclear structure physics. Experiments using protons as probes had showed that, like the Gamow–Teller resonance discovered earlier (*Physics News in 1980*, p. 63), the M1 resonance has considerably reduced strength. The reduction could be explained at least in part by the subnucleon spin degrees of freedom, specifically the spin excitation of delta particles in the nucleus (*Physics News in 1982*, p. 77).

The pion has also proved to be a useful probe of nuclear giant resonances. In one pion experiment physicists from Los Alamos and Tel Aviv measured the charge exchange reaction in which an incident π^- is converted into a π^0 while scattering from heavy nuclei.[4] They found a peak in the cross section which became prominent at a scattering angle of zero degrees. This is interpreted as a signature of the isospin monopole giant resonance, which is a radial displacement of neutrons with respect to the proton position.

In two recent experiments, the giant dipole resonance was identified in highly excited nuclei, showing that coherent dipolar motion can persist in a hot nuclear environment. The experimental signature for the resonance was the emission of energetic gamma rays (10–25 MeV), peaking at an energy corresponding to the vibrational frequency of the resonance.

Two physical mechanisms have been employed to produce the gamma rays. One technique uses collisions between complex projectiles and various target nuclei. Researchers at Lawrence Berkeley Laboratory studied the giant resonance in very heavy nuclei using a 1150-MeV Xe beam to excite the target nucleus.[5] At the University of Washington, researchers used beams of lighter ions such as ^{4}He and ^{12}C that fuse with the target.[6] In either case, the collision process produced a heated compound nucleus, in which part of the energy went into the giant-resonance vibrational motion.

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1. George Bertsch, Sci. Am. **248**, 62 (May 1983).
2. J. D. Walecka, in *Preludes in Theoretical Physics*, edited by A. de Shalit, H. Feshbach, and L. Van Hove (Interscience, New York, 1966).
3. N. Anataraman *et al.*, Phys. Rev. Lett. **46**, 1318 (1981).
4. J. D. Bowman *et al.*, Phys. Rev. Lett. **50**, 1195 (1983).
5. J. E. Draper *et al.*, Phys. Rev. Lett. **49**, 434 (1982).
6. D. H. Dowell *et al.*, Phys. Rev. Lett. **50**, 1191 (1983).

Dirac Equation

Nonrelativistic quantum mechanics, embodied in the Schrödinger equation, has been the basis of nearly all nuclear physics to date. This is because relativity was not expected to play an important role in nuclear physics: the binding in energies of nuclei (typically a few MeV) are small compared to their rest mass (typically many GeV).

Some nuclear phenomena, however, cannot naturally be accommodated in the nonrelativistic theory and must be treated with the Dirac equation, which takes into account the nucleon's spin, an important consideration, e.g., in the scattering of polarized protons from nuclei. Spin is basically a relativistic phenomenon—it is a key part of Dirac's theory—so the use of Dirac's equation is appropriate.

In the theory of proton scattering from nuclei, the traditional approach uses phenomenological potentials for the central and the spin-dependent fields. That is, the scattering, as portrayed in the Schrödinger equation, was taken to derive from two interaction terms. The spin-dependent part of the scattering (for protons in the energy range of 200–800 MeV) appears rather complicated in the Schrödinger framework, however, so the Dirac equation was used instead, with good result.[1]

The Dirac theory also requires two potentials to represent the interaction: an attractive scalar part and a repulsive vector part, which correspond respectively to the exchange of scalar and vector mesons. Such exchanges are often used to characterize the nuclear force. Both potentials are quite strong, but they cancel, so that the apparent nonrelativistic potential is weak and gives small binding energies. Of course being purely phenomenological, with parameters of the potentials adjusted to fit the data, the theory was not complete.

Recently, the parameters of the Dirac potentials were derived directly from nucleon–nucleon scattering data, using the technique of the impulse approximation,[2] a technique in which proton–nucleus scattering is attributed to quasifree scattering from individual nucleons inside the nucleus. Thus, the scattering data and related spin properties are explained with no free or *ad hoc* parameters.

Others have shown that the Dirac approach to the nucleus also gives a natural explanation of saturation, the apparent growth, rather than collapse, of the nucleus as particles are added to it.[3,4] Saturation arises from the relativistic dynamics by the weakening of the attractive scalar terms in the two cancelling interactions as the nuclear density is increased.

By extending the underlying dynamics to a relativistic treatment, nuclear theory has taken an important step in realizing the goal of understanding the properties of the nucleus in terms of the interactions among its constituents.

R. Amado, University of Pennsylvania
S. Wallace, University of Maryland

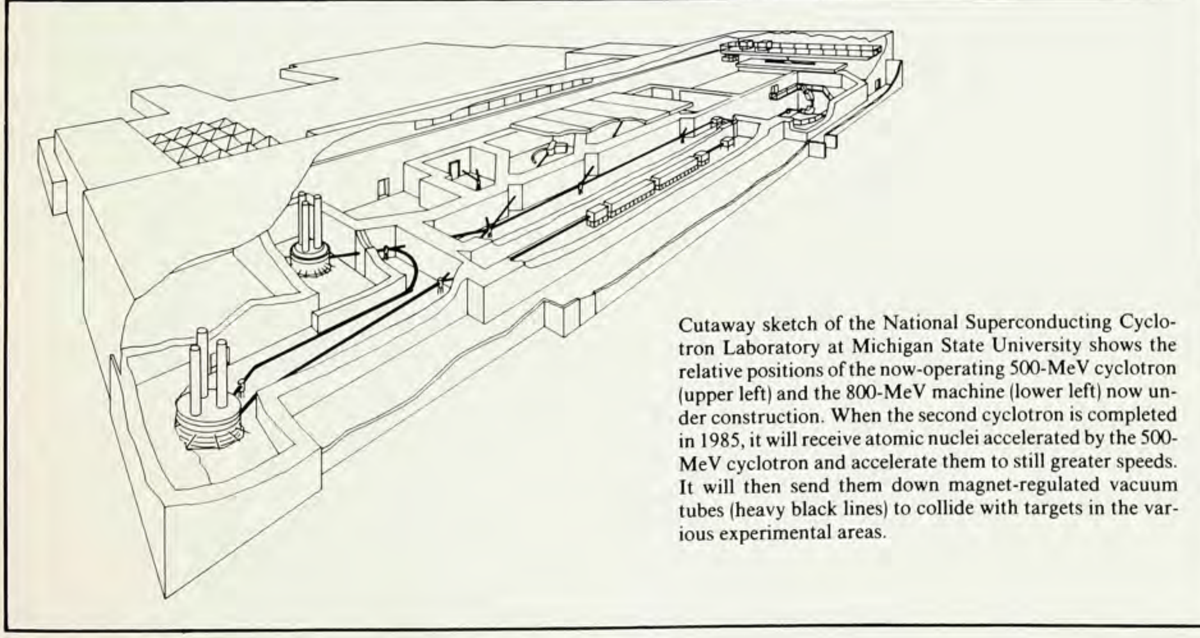
1. L. G. Arnold, B. C. Clark, R. L. Mercer, and P. Schwandt, Phys. Rev. C **23**, 1949 (1981).
2. J. McNeil, J. Sheppard, and S. Wallace, Phys. Rev. Lett. **50**, 1439 (1983).
3. J. D. Walecka, Ann. Phys. (N.Y.) **83**, 491 (1974).
4. L. S. Celenza, B. Goulard, and C. M. Shakin, Phys. Rev. D **24**, 912 (1981).

Nuclear Deexcitation by Fragmentation

Much of our present understanding of nuclei comes from studying the decay properties of radioactive or excited nuclei. In fact, the radiations emitted by long lived "radioactive" nuclei were discovered well before the concept of the atomic nucleus was developed. The classical forms of nuclear radiation are known as alpha, beta, and gamma radiation, corresponding to the emission of ^{4}He nuclei, electrons or positrons, and photons by the radioactive nucleus. In addition, heavy nuclei were discovered to decay by fission almost half a century ago. In this latter process, the unstable nucleus divides into two heavy fragments of comparable mass. During the last 30 years, little has changed in this overall picture of nuclear decay. As the excitation energy of the atomic nucleus is raised to a few tens of MeV, the emission of gamma rays, neutrons, protons, and alpha particles and nuclear fission become the dominant decay modes. At even higher excitation energies, the various isotopes of hydrogen and helium can also be emitted as decay products.

Recent experiments indicate that the spectrum of particles which are emitted by nuclei of several hundreds of MeV excitation may include nuclear species that are considerably heavier than helium nuclei but considerably lighter than typical fission fragments: examples include oxygen or sulfur nuclei. More than ten years ago, the emission of such intermediate mass nuclei was observed for "spallation" reactions induced by protons of relativistic energies smashing into heavy target nuclei.[1] At such high energies, the amount of energy deposited in the heavy target nucleus is not known and it was conjectured that the nucleus is shattered or cut into pieces by the incident relativistic proton. More recently, the emission of intermediate mass fragments was also observed in experiments performed with relativistic heavy ion beams at the Berkeley Bevalac Accelerator,[2] indicating these fragments are emitted in a wider class of nuclear reactions.

During the last year, several theoretical investigations concluded that the emission of intermediate mass fragments should be a more general property of the decay of high excited nuclei.[3] If the "temperature" of a nucleus is raised to about 5–10 MeV (or, equivalently, to about 50–100 billion degrees), it should cool by not only emitting light particles such as hydrogen or helium isotopes, but also by emitting heavier nuclei such as carbon, oxygen, neon, and so forth. These qualitative predictions seem to be confirmed in a recent experiment performed at the new superconducting cyclotron at Michigan State University.[4] By bombarding silver and gold target nuclei with carbon projectiles of 15- and 30-MeV nucleon inci-



Cutaway sketch of the National Superconducting Cyclotron Laboratory at Michigan State University shows the relative positions of the now-operating 500-MeV cyclotron (upper left) and the 800-MeV machine (lower left) now under construction. When the second cyclotron is completed in 1985, it will receive atomic nuclei accelerated by the 500-MeV cyclotron and accelerate them to still greater speeds. It will then send them down magnet-regulated vacuum tubes (heavy black lines) to collide with targets in the various experimental areas.

dent energy, one does not expect to achieve maximum nuclear temperatures about 10 MeV. If all target and projectile nucleons share the available excitation energy, temperatures between 3.5 and 6.5 MeV should be achieved in these reactions. The investigation revealed that intermediate mass fragments are indeed emitted with considerable probability. At the same time, the energy spectra and angular distributions of the emitted particles give strong evidence that the nuclei do not reach their equilibrium configuration before they decay. The decay by particle emission already sets in before the excitation energy is distributed over the entire nucleus. Eventually the study of these new decay phenomena may provide new insights about the properties of nuclear matter at extremely high temperatures as they might have existed during the early stages of the universe or in supernova explosions. Several new accelerators are under construction or are starting operation which will be ideally suited for these investigations.

C. K. Gelbke, Michigan State University

1. A. M. Poskanzer, G. W. Butler, and E. K. Hyde, Phys. Rev. C **3**, 882 (1971).
2. H. H. Gutbrod, A. I. Warwick, and H. H. Weiman, Nucl. Phys. A **387**, 177c (1982).
3. W. Friedman and W. G. Lynch, Phys. Rev. C (to be published).
4. C. B. Chitwood, D. J. Fields, C. K. Gelbke, W. G. Lynch, A. D. Panagiotou, M. B. Tsang, H. Utsunomiya, and W. A. Friedman, Phys. Lett. B (to be published).

Shell Orbits Visualized

Information from electron scattering experiments provides precise determination of the distribution of charge in nuclei. The observed charge density is quite smooth in the interior of the nucleus, and falls off over a distance of 1 fm (10^{-15} m) at the nuclear surface. Current understanding of these densities is based on the Brueckner–Hartree–Fock theory. This theory works remarkably well in reproducing the experimentally observed shape of the charge density in the surface region, but it is not quite as successful for the interior density. In Hartree–Fock theory, the nucleons occupy shell orbits, analogous to electron orbits in atomic theory; the density distribution can be described in terms of the wave functions (the mathematical expression of the nucleon's quantum behavior) which correspond to the orbits. The densities have significant fluctuations, with minima at the nodal points (zero points) of the wave functions. The empirical density distributions from electron scattering, however, show much less fluctuation in the interior.

A recent high-precision experiment in electron scattering[1] has clarified the situation by focusing on a specific orbit in a heavy nucleus. A research collaboration from Saclay and Basel, working at the Saclay linear electron accelerator, measured 500-MeV electron scattering from targets of ${}^{205}_{81}\mathrm{Tl}$ and ${}^{206}_{82}\mathrm{Pb}$, and compared the charge densities. The two nuclei differ in the shell model only by the presence of an extra proton in the 3*S* orbit in the lead nucleus. The relative charge density should then directly measure the spatial distribution of a 3*S* particle. The experimenters found that the observed radial distribution had the expected three peaks of a 3*S* wave, but the amplitude of the fluctuation was reduced from that expected for a pure shell wave function. The data could be explained if the extra proton were in the 3*S* orbit only 70% of the time, and were smoothly distributed on other orbits for the remainder. Such mixing of the wave function is in fact not surprising; the strong short-range correlations between nucleons reduce the probability that nucleons will be found in the shell orbits by about that amount. But these correlations are not expected to have such a visible effect on the charge densities. The experiment showed in a direct way both the physics of shell orbits and the violations of the shell model that must be present in a more complete theory.

George Bertsch, Michigan State University

1. J. M. Cavedon *et al.*, Phys. Rev. Lett. **49**, 978 (1982).

OPTICS

Optics is the study of the generation, transmission, and detection of light. In addition to the traditional areas of optics research, such as microscopy, diffraction, spectroscopy, and polarization, interest has also centered on such fields as holography, metrology (the science of measurements), solar energy conversion, and medical diagnostics. Detectors capable of counting individual photons and powerful lasers have made new discoveries possible.

Another area of increasing importance is the use of light in communications. The technologies of fiber optics and optical integrated circuits are developing rapidly. One mark of progress in this field is the development at Bell Labs of a "cleaved-coupled-cavity" laser, nicknamed C^3 laser, which has transmitted data at a rate of 10^9 bits per second over 104 km of optical fiber, with an error rate of less than 1 in 10^9, and with no reamplification along the way.[1] At this rate one could transmit the entire text of the Encyclopedia Britannica in less than half a second.

1. Phys. Today **36**, 20 (October 1983).

Vacuum Ultraviolet and Extreme Ultraviolet Generation with Excimer Lasers

High spectral brightness rare gas–halogen (RGH) sources have been used to generate coherent radiation in the extreme ultraviolet by harmonic generation mechanisms (in which long-wavelength light is converted into shorter-wavelength light) and by direct multiquantum excitation of appropriate gain media. In order to demonstrate the basic characteristics of these two approaches, recent comparative measurements have been made by a team of scientists at the University of Illinois at Chicago.

With the use of a 4-GW (gigawatt) argon–fluoride laser (at a wavelength of 193 nm) operating at a pulse duration of about 10 psec, they studied harmonic generation in several atomic and molecular media, creating beams at 64.3 nm (20 kW) and 38.6 nm (200 W). In addition, stimulated emission in molecular hydrogen has resulted in the generation of radiation as short as 117.6 nm at an efficiency on conversion approaching 1%.

Strong stimulated emission in the extreme ultraviolet following multiphoton excitation of krypton atoms using a 193-nm ArF* excimer laser has also been observed.[1] The ArF* laser pulse,[2] with an output power of 1 GW and 10-psec duration, was focused into a differentially pumped cell similar to the one used for harmonic generation in the extreme ultraviolet.[3] With Kr pressures between 100 and 1000 Torr, stimulated emission in krypton at 93 nm was observed.

The maximum efficiency observed in the initial experiments for conversion to 93 nm from the excitation at 193 nm corresponds to about 10^{-4}. Latest results indicate that it may be possible to increase the efficiency by one to two orders of magnitude. This system appears to be the first true laser emission in the extreme ultraviolet.[4]

C. K. Rhodes, University of Illinois at Chicago

1. T. Srinivasan, H. Egger, T. Luk, H. Pummer, and C. K. Rhodes, in *Laser Spectroscopy VI, Proceedings of the Sixth International Conference at Interlaken*, edited by W. Weber and W. Luthy (Springer, New York, to be published).
2. H. Egger, T. S. Luk, K. Boyer, D. F. Muller, H. Pummer, T. Srinivasan, and C. K. Rhodes, Appl. Phys. Lett. **41**, 1032 (1982).
3. H. Egger, R. T. Hawkins, J. Bokor, H. Pummer, M. Rothschild, and C. K. Rhodes, Opt. Lett. **5**, 282 (1980).
4. Phys. Today **36**, 19 (November 1983).

Direct Addressing of Logic Circuits by Picosecond Optical Pulses

The direct addressing of ultrafast integrated circuits by picosecond optical pulses has numerous applications in electronics and data processing. These include new and unambiguous ways of characterizing the speeds of gigahertz (10^9 operations per sec) logic circuits, contact-free diagnosis of problems or failures in complex circuits, and the presentation of novel possibilities for data input and interconnections in future high-speed data processors and supercomputers.

Scientists at Hughes Research Laboratories have recently used 5-psec light pulses from a dye laser to directly address and control relatively simple gallium–arsenide field-effect-transistor (FET) logic circuits, such as NOR gates, inverters, and *D* flip-flops.[1,2] Photoconductivity within these circuits was used as the detection mechanism. This leads quite easily to the generation of on-chip logic level pulses with only 1 mW of average optical power. Light-induced control of logic operations has also been demonstrated; the light pulse behaves as a logic "1" input in such "opto-electronic" circuits.

One convincing example of the utility of light-induced picosecond logic level pulses was the recent measurement of propagation delays in a gigahertz clock-rate *D* flip-flop by a picosecond logic sampling technique.[3] These experiments simply required the measurement of the average (electrical) power at the output of the *D* flip-flop as a function of the temporal delay between a pair of picosecond optical pulses that address the circuit. A flip-flop latching time of about 450 psec and a single NOR gate delay of about 90 psec was inferred from such measurements without the use of any high-speed electronic instrumentation.

Such logic sampling techniques, based on picosecond optical input, not only circumvent problems related to the coupling of high-speed signals to and from the GaAs chip (and the related problem of parasitics and loading), but also provide an unambiguous determination of the gate delay (in contrast with the conventional ring oscillator and gigahertz-rate "divide-by-two" techniques). Numerous variations of these optical techniques are currently being implemented at Hughes for the direct measurement of on-chip propagation delays and waveforms in gigahertz logic circuits with unprecedented (10-psec) resolution and accuracy.

From a long-term perspective, the optical addressing of logic circuits (particularly with compact semiconductor lasers that may be integrable with semiconductor chips containing the integrated circuits themselves) also has several important applications in future high-speed data processors. For instance, present speed bottlenecks in high-speed computers may be alleviated with the use of hybrid electro-optical data processors, in which data transmission between various points on high-density integrated circuits would occur via ultrashort light pulses and imaging holographic interconnections.

R. K. Jain, Hughes Research Laboratories

1. R. K. Jain and D. E. Snyder, Opt. Lett. **8**, 85 (1983).
2. R. K. Jain and D. E. Snyder, IEEE J. Quantum Electron. QE-19, 658 (1983).
3. R. K. Jain and D. E. Snyder, Paper THG4 presented at Conference on Lasers and Electro-Optics, Baltimore, Maryland, May 1983.

Broadband Optical Frequency Shifters

With few exceptions, the frequency of an optical wave can be shifted, using the acousto-optic effect, by reflection from a traveling acoustic wave in materials like quartz or lithium niobate. If the light is incident on the acoustic wavefront at a special angle called the Bragg angle, then at moderate acoustic power the reflected light wave contains practically all of the incident optical energy, with a frequency shift determined by the acoustic frequency. Consider laser light: There will be an upshift if the laser beam reflects off the front of the propagating wave or a downshift if it reflects from a receding wave.

Optical frequency shifters are used to supply tunable local oscillators in laser heterodyne systems, displaced frequencies for counter-propagating waves in laser gyros, and ultraprecise variable frequency sources using a fixed laser frequency standard.

A new type of frequency shifter using the Bragg effect has been demonstrated at the MIT Lincoln Laboratory. This device has a fixed input angle and yet operates over a range from hundreds of megahertz down to arbitrarily low frequencies. The significant difference is the use of the electro-optic rather than the acousto-optic effect. An array of electrodes is driven in three phases, just as in a linear induction motor, so that the laser beam propagation in a slab waveguide beneath the electrodes sees a propagation wave just as in the acoustic case.[1] The wavelength is fixed, however, and in the reported work, the electrode spacing of 6 μm results in a wavelength of 18 μm and an external input angle into the slab waveguide of 1.0°. Over 90% conversion efficiency has been obtained at 100 MHz. Randomly scattered carrier power was well below 1% of the single-sideband or frequency-shifted output.

R. H. Kingston, Lincoln Laboratory, MIT

1. R. H. Kingston, R. A. Becker, and F. J. Leonberger, Appl. Phys. Lett. **42**, 759 (1983).

PLASMA AND FUSION PHYSICS

Plasma is an unusual state of matter, a sort of superhot, highly ionized gas containing equal numbers of positively charged ions and negatively charged electrons. Plasmas exist in interstellar space, percolate inside stars, and spread out across the northern sky in the form of auroras.

Perhaps the most important area of plasma research is the attempt to initiate fusion reactions, such as those which occur inside the sun, for the purpose of commercial power production. A great deal of energy can be released in the fusion of two nuclei, but in order to get energy out, energy must first be put in. Before the nuclei can interact via the strong nuclear force, the comparatively weaker (but still formidable) electrostatic force of repulsion between the nuclei must be overcome. So, in order to begin producing energy (17 MeV per reaction in the case of deuterium–tritium fusion), the nuclei must themselves possess large kinetic energies (thousands of electron volts for D–T). Equivalently, the sample of nuclei must be at very high temperatures (100 million degrees for D–T).

Several schemes have been devised to heat, and afterwards to confine, plasmas in terrestrial reactor vessels. In magnetic confinement, the plasma is held within a "magnetic bottle," a region of space surrounded by current-carrying coils that produce magnetic fields which deflect wayward particles from the walls of the vessel. The tokamak is a fusion reactor with a toroidal shape. In the past year the two largest tokamaks have begun operating. These are the Tokamak Fusion Test Reactor at Princeton[1] and the Joint European Torus in England.[2]

Another magnetic confinement scheme is the open-ended cylindrical reactor with magnetic "mirrors" at both ends (*Physics News in 1982*, p. 96). The leading mirror machines are the Mirror Fusion Test Facility at Livermore[3] and Phaedrus at the University of Wisconsin. Other magnetic confinement devices include the Elmo Bumpy Torus at Oak Ridge (*Physics News in 1982*, p. 94), the Stellarator at Wisconsin (*Physics News in 1981*, p. 96), and the Reversed Field Pinch machine at Los Alamos.

In inertial confinement schemes, a small target pellet is bombarded by laser light or particle beams from many sides simultaneously. The implosion of the fuel material heats it to fusion temperature. The principal laser-fusion devices are NOVETTE/NOVA at Livermore[4] and HELIOS/ANTARES at Los Alamos. The Particle Beam Fusion Accelerator at Sandia (*Physics News in 1982*, p. 97) employs beams of light ions as the "driver" for fusion. The use of heavy ions will be described in an article below.

Phillip F. Schewe

1. Phys. Today **36**, 17 (March 1983).
2. Phys. Today **36**, 22 (August 1983).
3. T. C. Simonen *et al.*, Phys. Rev. Lett. **50**, 1668 (23 May 1983).
4. John Nuckolls, Phys. Today **35**, 24 (September 1982).

Muon-Catalyzed Fusion

It has long been recognized that fusion reactions could possibly occur at low temperatures if the electrons in the hydrogen fuel were replaced by muons allowing the nuclei to approach much closer before electrostatic repulsion takes over.[1] This would alleviate the need for such high energies (or, equivalently, high temperatures) in fusion reactors.[2]

In deuterium–tritium (DT) fusion, muons injected into a mixture of D and T were expected to form closely bound DTμ "mesomolecules" which then undergo fusion into an alpha particle and a neutron, springing the muon free to catalyze another reaction. Unfortunately, early calculations showed that the DTμ formation time was so long that on the average only one reaction could be catalyzed during the 2-μsec lifetime of a muon, and the energy released would fall far short of the energy required to create the muon in the first place.

Recent work in the USSR and elsewhere has revived interest in this subject by pointing out that the DTμ formation rate is much larger than previously thought, owing to a fortuitous coincidence between an excited level of the DTμ mesomolecule and a level of the DTμ–D or DTμ–T molecular complex formed when a mesic triton Tμ combines with a D_2 or DT molecule. A single muon could then catalyze 100 to 1000 reactions, provided that it could be freed from capture by the resultant alpha particle, in which case the process would be energy efficient.[3]

This new prediction has been checked experimentally by scientists from the Idaho National Engineering Laboratory (INEL) and Los Alamos at the Clinton P. Anderson Meson Physics Facility.[4] Using DT targets 0.6 times as dense as liquid hydrogen, they found that 70 DT fusions were produced per muon at 127°C, well below the 10^8 °C temperatures required in conventional plasma fusion. The results were even more optimistic than the predictions: The fusion yield was nearly twice as large as expected, and the χ-particle sticking coefficient somewhat smaller than expected. Because the DTμ formation rate is temperature dependent, a peak infusion neutron yield was expected at 270°C. A temperature dependence was indeed observed, but the yield seemed to be still rising at this temperature.

Further experiments and more refined calculations are being carried out seeking agreement with regard to the temperature dependence, which is a critical test of the resonant formation of DTμ mesomolecules. The alpha-particle sticking coefficient is now the bottleneck, and methods are being considered for releasing the muon after alpha capture. The feasibility of "cold" fusion apparently has been revived.

Steven Jones, Idaho Engineering Laboratory

1. L. W. Alvarez *et al.*, Phys. Rev. **105**, 1127 (1957).
2. J. D. Jackson, Phys. Rev. **106**, 330 (April 1957); L. Bracci and G. Fiorentini, Phys. Rep. **86**, 169 (1982).
3. Yu. V. Petrov, Nature **285**, 466 (1980).
4. S. E. Jones *et al.*, Paper presented at the *Third International Conference on Emerging Nuclear Energy Systems*, Helsinki, Finland, June 1983.

Fusion Reactors With Spin Polarized Nuclei

A fundamental parameter for nuclear fusion reactors is the nuclear cross section, a measure of the probability that a nucleus will undergo a fusion reaction with another nucleus. It is well known to nuclear physicists that this happens to depend on the relative orientation of the nuclear spins just prior to the interaction. However, because of the difficulty of orienting spins of nuclei in any quantity and because of the likelihood that under the intense conditions present in a nuclear fusion reactor the nuclei could not remain polarized for very long, the possibility of polarizing spins to enhance the rate of nuclear reactions had largely been ignored until a year ago.[1]

Calculations at Princeton have shown that the rate of loss of polarization would actually be very low under expected reactor operating conditions. Consider the case of two important fusion nuclei, tritium and deuterium. An appreciable fraction of the polarization can be maintained for about 10^5 sec in the case of tritium and about 10^6 sec for deuterium. It was also found that by making use of modern techniques, it was now possible to produce large quantities of polarized deuterons or tritons efficiently and cheaply.

These two facts—the apparent slow rate of depolarization and the possible availability of sufficient quantities of polarized nuclei in a gaseous or solid form—make polarization an attractive technique for improving reactor performance.

The potential advantages of operating a fusion reactor with polarized nuclei are as follows. For a DT reactor (one using deuterium–tritium reactions) with the spins of D and T nuclei both polarized parallel to the magnetic field, the effective nuclear cross section is 50% larger than for unpolarized nuclei. Thus, the nuclear reactivity is increased by 50%. For the same conditions, 50% more nuclear power would be produced in the reactor, or, if the limitation on the total pressure desired in a reactor were serious, one could operate at lower pressure and attain the same nuclear power. The neutrons and alpha particles (helium nuclei) resulting from fusion reactions would be emitted predominantly perpendicular to the magnetic field. This could have advantages for alpha particle trapping in mirror machines. Also the directivity of the neutrons could be employed to avoid damage to various surrounding walls and equipment, extending their lifetime.

The emission of the alpha particles in the perpendicular direction produced as a result of polarizing the D and T nuclei along the magnetic field direction is actually a disadvantage in tokamaks since it makes them more difficult to contain. An actual improvement in alpha particle confinement could be obtained, however, by polarizing only the spin of the D nucleus perpendicular to the magnetic field direction and not polarizing the T nuclei at all. For this polarization configuration, the nuclear reaction rate is the same as for an unpolarized reactor, but the alpha particles are emitted predominantly along the magnetic field direction, easing their confinement problem.

Another possible application of polarization to future nuclear fusion reactors is based on the possibility that the D–D reaction can be *suppressed* by polarizing the D nuclei parallel to the magnetic field direction. This method of polarization could be employed in a D–He[3] reactor in which the only source of neutrons is the D–D reaction. The D–He[3] reactor could thus be a neutron-free reactor.

The question of whether polarization would actually work in a nuclear reactor has to be settled by direct experiment.[2] There are many possible sources of depolarization other than collisions. Theoretically, it appears possible to avoid the more dangerous ones, such as wall effects and magnetic fluctuations occurring at the precession frequency (the natural resonance frequency for a polarized nucleus in a magnetic field). When adequate sources of polarized nuclei become available current experimental devices can be used to test the depolarization rates directly. It is hoped that these experiments will be carried out within a year or two.

Russell Kulsrud, Princeton Plasma Physics Laboratory

1. Phys. Today **35**, 17 (August 1982).
2. New Sci. **97**, 581 (3 March 1983).

Chaos and Plasma Physics

In recent years there have been significant advances in the study of transition from order to chaos in a variety of systems (*Physics News in 1982*, p. 47; *Physics News in 1981*, p. 34). Plasma physicists are active participants in this interdisciplinary venture and numerous applications in plasma physics are emerging.

The problem of transition of a physical system from order to chaos is an old one. Water pumped through a pipe slowly, for example, exhibits regular laminar flow; fast pumping leads to turbulence. Waves break on a beach converting regular wave motion into chaotic motion. In fusion systems one wants to heat a plasma to a high temperature. This may be accomplished by injecting an electromagnetic wave into the plasma, converting the ordered wave motion into the chaotic motion of plasma particles (namely, heat).

In classical mechanics the motion of a system of particles is described by differential equations. A few of these problems, called integrable problems, can be solved analytically. For example, the motion of the Earth around the sun (ignoring the influence of the other planets and the moon) yields a well-defined elliptical orbit. Once a third body like the moon is added, however, the problem becomes nonintegrable. Physicists describe the motion in an abstract space, the phase space, where the coordinates include the velocities as well as the positions of all particles. It can be shown that, for an integrable system, the orbits in phase space (for instance, a three-dimensional one) are lines wrapped on a doughnut-shaped torus.

An important breakthrough came in the 1960's, with a mathematical theorem developed by Kolmogorov, Arnold, and Moser known as the KAM theorem,[1] which holds that once a small amount of nonintegrability is introduced (such as by adding a light moon to the sun–earth system), some orbits will continue to lie on a torus, but many will be chaotic insofar as motion is unpredictable (like a ball landing on a roulette wheel). The chaotic motion is not exactly calculable because if you started from a slightly different position or with slightly different velocity, the orbit would, in the long run, be very different.

The laws of classical mechanics have traditionally been deterministic (exactly predictable motion), in marked contrast with quantum theory where predictions are only statistically, not individually, reliable. This distinction has been significantly weakened by modern chaos theory. While it is still true that, given the exact initial positions and velocities of all objects, the orbits are calculable, the slightest errors in these data (or the fact that computers carry only a finite number of digits) can lead to entirely different orbits in most systems. This extreme sensitivity to initial conditions characterizes chaos in classical mechanics.[2]

At the present time no mathematical theory exists to treat strongly nonintegrable systems like our solar system or a galaxy, but one can analyze chosen problems on computers and arrive at conclusions that may lead to exact theories. Plasma physicists have made significant contributions in this area. The motion of a particle under the simultaneous influence of many wave fields is an example of a nonintegrable system. How strong must the waves be so that most of phase space is chaotic, allowing some particles to keep gaining energy from the waves? Such energy gain can occur only if a class of orbits producing regular tori are destabilized, because they form barriers in phase space that chaotic orbits cannot penetrate.[3] In some cases the boundaries of chaotic motion can be predicted with arbitrary accuracy.[4] This is facilitated by an interesting geometrical property of orbits in phase space known as self-similarity on all scales, a phenomenon in which some geometrical structures have elements that exhibit the same structure under magnification, and so on. This is the reason why the techniques of renormalization theory[5,6] and fractals[4,7] are such powerful tools in this field.

While computations give valuable insights into how a system behaves, one would like to develop methods valid for all systems. In the late seventies Mitchell Feigenbaum[8] showed that certain mathematical treatments of chaos had universal features. Similar features were subsequently discovered in nonintegrable dynamical systems.[9]

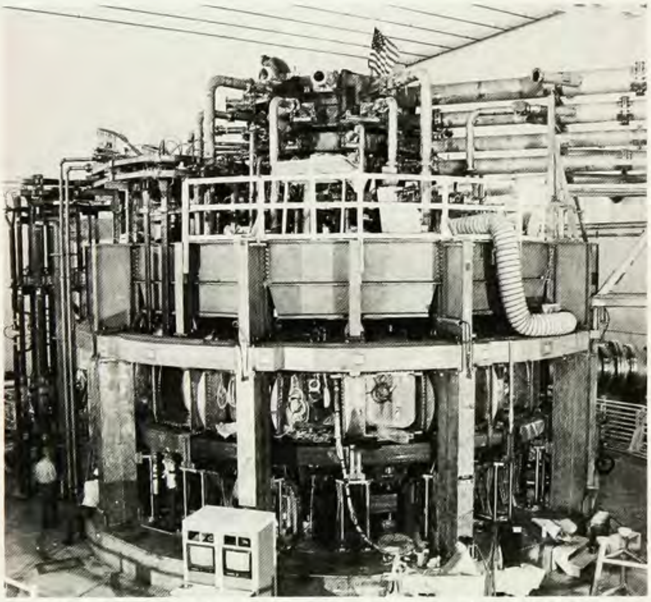
Considering the practical aspects of these theories for designing fusion devices, one notes the geometric analogy between integrable trajectories in phase space and the magnetic field lines in real space (also lines wrapped on tori) in tokamaks and stellarators. Errors in coil manufacture might result in chaotically wandering field lines between regular tori, which would be harmful for plasma confinement. Such effects are being studied to minimize the energy loss of the fusion plasma.[10]

George Schmidt, Stevens Institute of Technology

CHAOS IN A CHEMICAL REACTION

Our cover illustration shows a phase-space portrait of an oscillating chemical reaction, one in which the concentration of a particular chemical in the solution is measured at discrete time intervals. This plot consists of some 33,000 points, whose x and y coordinates are, respectively, the concentration at a time **t** and the concentration at a time **t + T**, where T is a fixed time delay parameter. If this system were periodic—that is, if the concentration rose and fell in a rhythmic cycle—its behavior would be represented by a single loop, called a limit-cycle attractor, which is retraced over and over again as time goes by. Instead, the system depicted in the figure is chaotic. Its nonperiodic behavior unfolds in the form of a single convoluted curve that appears as a series of looping orbits. The figure shows about 250 such orbits; if the system were monitored for longer periods of time much of the space between the orbits would gradually fill up. The resultant trajectory, called a "strange attractor," constitutes a curve with a nonintegral dimensionality. (See "Fractals" in *Physics News in 1981*, p. 58.) The study of chaotic systems has made great progress in recent years. *Chaos* is defined as nonperiodic behavior caused by the inherent, nonlinear nature of a system, as distinct from *noise*, which is nonperiodic behavior resulting from a stochastic (random) driving force, such as thermal agitation. Many scientists now believe that chaotic behavior can be characterized by deterministic coupled nonlinear differential equations and that these equations may be universally applicable to such disparate systems as weather, fluid flow, Josephson junctions, and fibrillating hearts. Short-term temporal evolution of such systems can be accurately predicted, as the highly ordered structure of the phase protrait suggests. Long-term behavior, however, is unpredictable because nearby points on the strange attractor trajectory separate (exponentially) rapidly as time evolves. Thus, even though the system is deterministic—that is, described by deterministic differential equations—long-term predictability would be possible only if the initial conditions were known to infinite precision. The figure was supplied by Harry Swinney of the University of Texas.

1. M. V. Berry, in *Topics in Nonlinear Dynamics* (American Institute of Physics, New York, 1978), Vol. 46, p. 16.
2. A. J. Lichtenberg and M. A. Lieberman, *Regular and Stochastic Motion* (Springer, Berlin, 1983).
3. J. Greene, J. Math. Phys. **20**, 1183 (1979).
4. G. Schmidt, Phys. Rev. A **22**, 2849 (1980); and G. Schmidt and J. Bialek, Physica **5D**, 397 (1982).
5. D. F. Escande, F. Doveil, Phys. Lett. A **83**, 307 (1981).
6. Critical Phenomena and Series Expansions, *Physics News in 1981*, p. 66.
7. Fractals, *Physics News in 1981*, p. 58.
8. Sci. Am. 245, 22 (November 1981).
9. J. M. Greene, R. S. MacKay, F. Vivaldi, and M. J. Feigenbaum, Physica 3D, 468 (1981).
10. R. B. White, PPPL-1984 (1983).



Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory, where the first test plasma was achieved in December 1982. The first deuterium–tritium breakeven experiments are scheduled for 1986.

Heavy Ion Inertial Fusion

Three key technologies must be developed to establish the feasibility of inertial-confinement fusion (ICF) power plants: reactors, targets, and drivers.[1] Much of the reactor and target research is independent of the choice of driver; however, the commercial utility of ICF is strongly dependent on the choice of driver. Both lasers and ion accelerators are driver candidates. Recent calculations and more than 50 years of experience with accelerators indicate that heavy-ion accelerators may be uniquely attractive for ICF power production.[2]

According to current calculations, the driver must deliver several megajoules of energy and a peak power of more than 100 TW (10^{14} W) at an efficiency of 10% to 20%. The beams must focus to spots a few millimeters in diameter across a 5-m reactor cavity, while the driver must fire 10 to 20 times per sec. The driver should be reliable and have a lifetime of about 30 years (unless it can easily be replaced at low cost). To be competitive with other sources of energy, the driver should not cost more than a few hundred million dollars. Finally, the coupling of beam energy to the target must be efficient. Efficient coupling requires that nearly all of the beam energy be absorbed and deposited within about 0.1 g/cm^2 of the target surface. If even 1% of the beam energy penetrates deeply enough to preheat the fuel, efficient target compression is not possible.[3] Beam penetration of 0.1 g/cm^2 corresponds to a kinetic energy of about 10 MeV (10^7 eV) for light ions and about 10 GeV (10^{10} eV) for heavy ions. Thus 100 TW of beam power requires a current of about 10 MA (10^7 A) of light ions, but only about 10 kA of heavy ions. This factor of 1000 in current is one of the important differences between light- and heavy-ion fusion.

Although existing laser and light-ion drivers are essential for near-term target experiments, they cannot satisfy many of the ICF requirements listed above. New driver technologies must be developed for power production. Calculations show that multistage, heavy-ion accelerators operating at an ion kinetic energy of about 10 GeV can meet all of the ICF requirements. In fact, adequate energy, reliability, lifetime, pulse repetition rate, and efficiency either have been demonstrated or appear to be modest extrapolations of existing technology.

Limits on high peak power arise from the concomitant high space-charge density (packing a lot of particles together in a tight beam). Instabilities can increase the beam emittance (beam angular divergence times beam radius) so that the beam is lost from the accelerator or cannot be focused onto the target. This issue has been extensively studied analytically and numerically, but only recently have some scaled experiments been performed.[4] The work so far is encouraging, but experiments that more closely approach the scale of a fusion driver are necessary. Beam focusing has also been studied theoretically, but there are almost no relevant experiments.

In conclusion, current heavy-ion fusion studies and experiments are encouraging. The Office of Energy Research has initiated an accelerator research program to perform the experiments required to assess fully the potential of heavy-ion fusion as a commercial energy source. The core of the research program is an accelerator capable of heating a target to at least 50 eV. The accelerator, planned for completion in 1989, is called the high temperature experiment (HTE). Los Alamos National Laboratory and Lawrence Berkeley Laboratory are designing the HTE. Preliminary designs are similar to the ATA electron induction linac at Lawrence Livermore National Laboratory.[5] The ATA design current (10 kA) is also roughly the current required for heavy-ion fusion; however, space-charge problems are not as severe for electrons as for ions. The HTE will be large enough to provide firm data on high-power accelerators, beam focusing, beam-target coupling, and costs.

R. O. Bangerter, Los Alamos

1. J. H. Nuckolls, Phys. Today **35**, 25 (September, 1982).
2. Phys. Today **31**, 17 (February 1978).
3. R. O. Bangerter, *Proceedings of the Sixth International Workshop on Laser Interaction on Related Plasma Phenomena*, Monterey, California, 25–29 Oct. 1982.
4. Several articles on this topic will appear in the *Proceedings of the U.S. Particle Accelerator Conference*, Santa Fe, New Mexico, March 1983.
5. Phys. Today **35**, 20 (February 1982).

THE NOBEL PRIZE IN PHYSICS

The 1983 Nobel Prize for Physics was awarded jointly to Subrahmanyan Chandrasekhar of the University of Chicago and William A. Fowler of the California Institute of Technology, for work relating to the evolution of stars.

Explication of stellar evolution has been one of the greatest scientific success stories of the past half century. The transformations of stars, including our sun, are now better understood than the transformation of a tadpole into a frog. Two points of view have driven this advance: the microscopic, studying events on an atomic scale, and the macroscopic, treating a star as a whole.

In the microscopic domain it has been found that the process from which stars draw their energy—the fusion of light elements to form heavier elements—can take place along various pathways. Nuclei of elements like carbon and nitrogen can function much as catalysts do in a chemical reaction, accreting hydrogen nuclei and eventually returning them, fused into helium, to the gas. In other cases the intermediate nuclei may themselves be transformed. The amount of energy that a star can produce, and, hence, its temperature and general configuration, depends on a complex balance among the various processes.

The synthesis of nuclei is also interesting for its own sake. At the time of the original Big Bang, almost no matter was created in the Universe except hydrogen and helium. In the furnaces at the centers of ordinary stars, these elements were forged into heavier nuclei. The elements were spewed back into space when the stars exploded, eventually forming the gas clouds that coalesced to make our solar system and, ultimately, the substance of our bodies. Nucleosynthesis processes are so delicately balanced that if certain nuclei such as carbon had slightly different properties, most elements would never have been produced in abundance and life could not exist.

Very heavy elements like gold and uranium cannot be built up at the temperatures that prevail within an ordinary star. They must be created during the giant explosions of supernovas, when tremendous swarms of neutrons pile onto nuclei and build up massive clumps, before the unstable intermediate nuclei have time to disintegrate. Study of nucleosynthesis in supernovas may have something to teach us about the origins of our solar system.[1]

The macroscopic viewpoint takes all that as given. Once one knows the amount of energy that nucleosynthesis will yield under given conditions, one can calculate how the entire star will behave. The calculations are complex. It turns out that as a star burns up its initial stock of hydrogen it must contract, growing hotter and denser. Meanwhile the outer layers cool and expand, so the star appears as a red giant. As the last of the hydrogen is used up the star begins a complex evolution, perhaps including explosions, eventually turning into a super-dense white dwarf. At each point there must be a balance between the gravitational force that pulls the mass together and the gas pressure that tends to blow it apart (it is the failure of this balance that causes supernovas). In the more massive stars, ordinary gas pressure cannot hold out against gravity. These stars contract until the nuclei touch one another, merge with electrons, and form a solid body—a neutron star.

The greater the mass of a star, the higher must be its temperature if it is to maintain enough pressure to hold up its outer layers against gravitational collapse. In particularly massive stars, the temperature may get so high that many of the electrons move at velocities near the velocity of light. Therefore, they show an increase of mass, following the laws of relativity. The extra, relativistic mass has all the properties of ordinary mass, including gravitational influence. Thus even as the temperature increases under the pressure of gravity, the pull of gravity itself increases. For a star whose mass is above a certain limit, roughly 1.5 times the mass of our sun, equilibrium is impossible and the star must collapse into a point, a black hole.[2]

Fowler's contributions to our understanding of stellar evolution have been in the microscopic domain and have included both theoretical calculations and laboratory experiments on nuclear interactions. During the 1950s he and his co-workers helped to fill in many of the details of the main pathways of nucleosynthesis. His work has ranged from studies of the way particles in ordinary stars can build up intermediate elements such as carbon, to explication of the swift heavy-element processes in supernovas.

Chandrasekhar has done mathematical work, mostly in the macroscopic domain, covering many areas of astrophysics. In the field of stellar evolution he helped to explain how stars evolve into red giants and under what conditions neutron stars are formed. When he was a student in the 1930s he deduced that stars must collapse when their mass is beyond the limit mentioned above—"Chandrasekhar's Limit."[3] In recent years he has returned to the study of how the equations of relativity may be applied to very massive stars.

Spencer Weart, American Institute of Physics

1. Sydney W. Falk and David N. Schramm, Sky and Telescope **58**, 18 (July 1979).
2. Hugh M. Van Horn, Phys. Today **32**, 23 (January 1979).
3. Kameshwar C. Wali, Phys. Today **35**, 33 (October 1982).

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