

This golden age of solid-state physics

Theodore H. Geballe



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Michael Faraday (in 1843) was surprised to find the resistance of silver sulfide went down when the temperature went up; Hans Meissner (in 1929) was surprised to find that copper sulfide suddenly became a much better conductor than metallic copper at very low temperature (2 K); people through the ages (from 3000 BC to a very young Albert Einstein) have puzzled over why the compass does what it does. We now have a fairly fundamental understanding of why these things happen. Solid-state physics has been

able to show how real materials governed by the laws of quantum mechanics can behave in such a variety of ways. In doing so, it has enabled us to make useful predictions and to synthesize materials with unprecedented properties and it has enabled us to use some materials as a basis of new technologies, making possible new styles of life.

The province of solid-state physics has expanded to include the quantum liquids helium-3 and -4, as well as other liquids and glasses; the field is now more appropriately described as condensed-matter science. It is concerned with the states of condensed matter and their responses to external stimuli, with transitions from one state to another and with the underlying microscopic interactions. David Pines points out in his article on page 106 the unity that is introduced through the concepts of quasiparticles, collective modes and other elementary excitations.

More than 25% of the physicists in the US are condensed-matter specialists. The field accounts for about a third of all the research publications in physics. Much of the output of condensed-matter physics is funneled into other sciences, into branches of engineering—electrical, metallurgical and mechanical—and into related technologies. In particular, condensed-matter physics is also an integral part of materials science, an interdisciplinary research field in which the microscopic and phenomenological methods of physics are combined with engineering

The News of Radio

Two New Shows on CBS Will Replace 'Radio Theatre' During the Summer

Two new shows are announced by CBS to serve as summer replacements for the hour-long "Radio Theatre" on Monday evenings. The first to be heard at 9:30 P. M. will be "Mr. Tutt," based on the stories of the late Arthur Train. Willard Wright will have the title role and Arnold Perl will do the adaptations. It will make its debut next week. The second, to open on July 12, will be "Our Miss Brooks," with Eve Arden playing the role of a school teacher who encounters a variety of adventures. It will be written by Al Lewis and Lee Lobb, with Larry Beria serving as director. "Our Miss Brooks" will be offered at 9 P. M. Mondays.

A situation comedy with musical overtones, headlined by Mel Tormé, has been selected as the replacement for the Dinah Shore-Harry James program at 8 P. M. Tuesdays over NBC, starting next week. The supporting company will include Janet Waldo and John Brown, Harmon Alexander and Ben Perry will do the script. Frank Danzig will be the producer and Ben Elliott, the musical director.

Station WFUT, Fordham University's frequency modulation outlet, will observe the completion of its first year of operation today. Throughout the day there will be special programs to mark the occasion and a number of personages on local commercial stations will participate, including John McCaffrey, Eleanor O'Connell, Pat Barnea, Mary Quinn, Alma Dettlinger and Arlene Francis.

At 8:05 P. M. there will be a critical discussion of present-day radio, the members of the panel including the Rev. Robert I. Gannon, president of Fordham; Morris Novik, John Garrison and F. W. Carlington.

"On Your Mark," a new audience-participation item, will be added to WGR's schedule next Monday. It will be heard at 2:30 P. M. each weekday afternoon thereafter and will include prizes for questions which are correctly answered. Paul Luther will produce and announce the program.

George Shackley's original composition, "Anthem for Brotherhood," will have its first television

Beginning tomorrow, "Waltz Time" will be heard for a full hour for three successive Friday evenings at 9 o'clock over NBC.

A memorial tribute to Col. David Marcus, who died in action while commanding the Israeli forces on the Jerusalem front, will be presented at 10:03 this evening over WKCA. Gov. Thomas E. Dewey and Mayor O'Dwyer will be among the speakers to be heard by means of transmissions.

Station WNEW will transmit reports on traffic conditions on the major highways in the metropolitan area for those who plan to spend the holiday week-end out of town. On Friday, the reports will be heard on the hour at frequent intervals between 4 and 11 P. M. The same schedule also will be followed on Sunday and Monday afternoons and evenings.

"The Better Half," which is to go under commercial sponsorship on Sept. 16 over the Mutual network, will take to the air as a sustainer on Aug. 19.

A device called a transistor, which has several applications in radio where a vacuum tube ordinarily is employed, was demonstrated for the first time yesterday at Bell Telephone Laboratories, 463 West Street, where it was invented.

The device was demonstrated in a radio receiver, which contained none of the conventional tubes. It also was shown in a telephone system and in a television unit controlled by a receiver on a lower floor. In each case the transistor was employed as an amplifier, although it is claimed that it also can be used as an oscillator in that it will create and send radio waves.

In the shape of a small metal cylinder about a half-inch long, the transistor contains no vacuum, grid, plate or glass envelope to keep the air away. Its action is instantaneous, there being no warm-up delay since no heat is developed as in a vacuum tube. The working parts of the device consist solely of two fine wires that run down to a pinhead of solid semi-conductive material soldered to a metal base. The substance on

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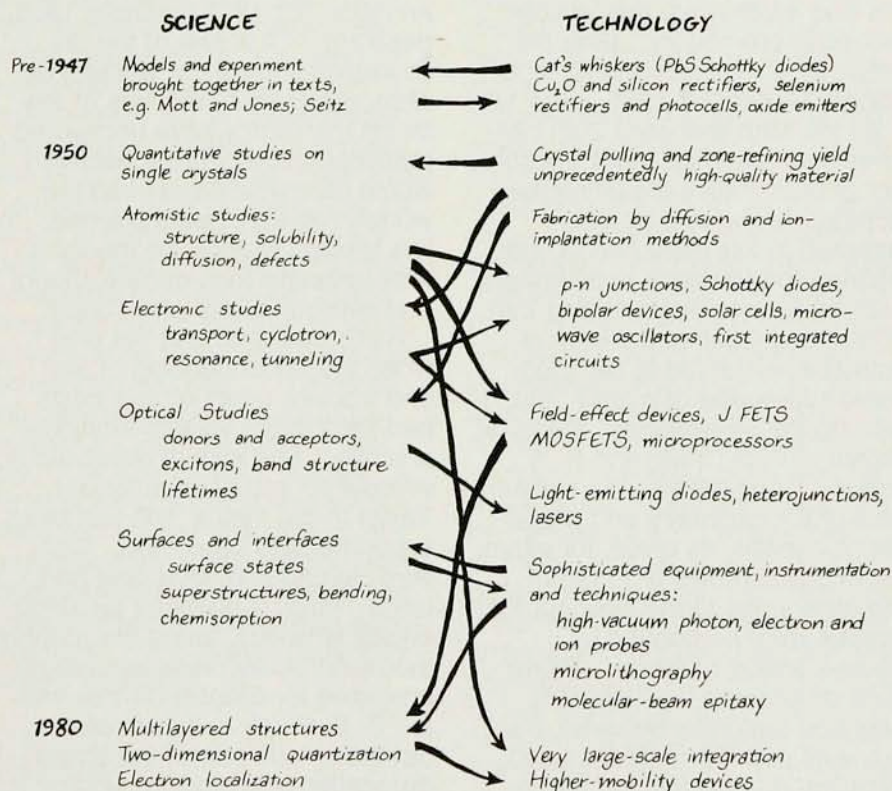
The discovery of the transistor, reported by The New York Times on 1 July 1948, evidently was considered almost as newsworthy as the replacement of Dinah Shore and Harry James by Mel Tormé.

Figure 1

empiricism and chemical concepts. Materials science seeks to synthesize materials in which the mechanical strength, electrical conductivity, optical and dielectric constants, and so on are determined by controlling defects, impurities, composition and structure. One of its many accomplishments is dislocation-free silicon for semiconductor processing. Another has been the development of molecular-beam epitaxy and the subsequent growing of multilayered semiconductor superstructures having energy gaps that vary periodically in one dimension; GaAs-GaAlAs and GaSb-InAs structures are examples discussed in a recent issue of *PHYSICS TODAY* (April 1979, page 20). Materials science is a major route by which the advances in condensed-matter physics diffuse into other science and technology.

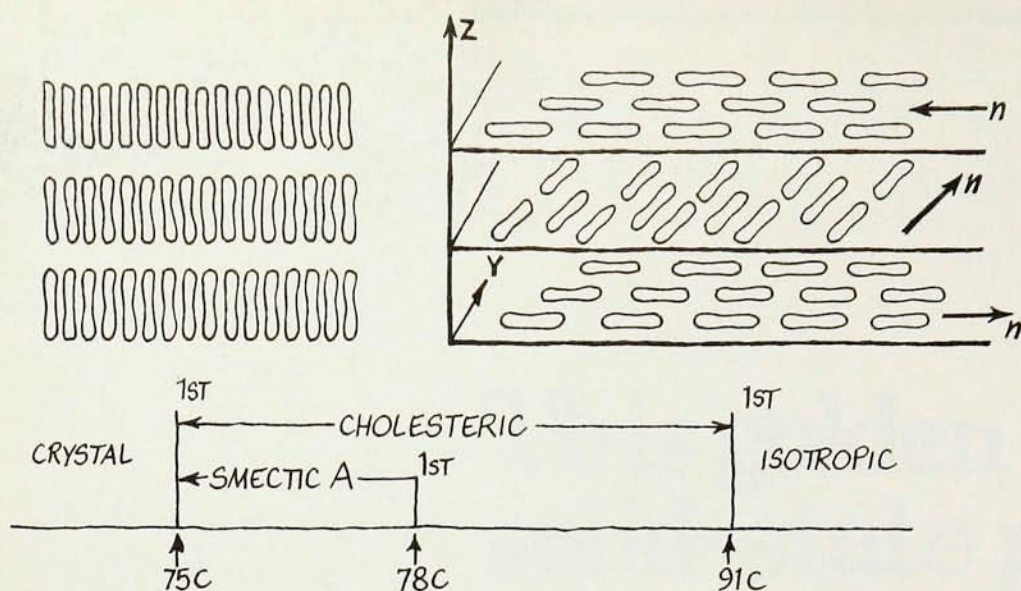
Pre-history and the years up to 1912

Evidence from the stone age shows that our ancestors learned how to fabricate flint tools as long ago as 10^5 to 10^6 years; they may not have known about stress concentration but they found out how to cleave nonetheless. The use of fire in the production of metals from minerals goes back about 10^4 years. Our ancestors learned that swords can be beaten into plowshares, that some metals are noble and can be used for creating art and preserving wealth, that a mixture of sand and ash can be turned into transparent glass. All



Synergism between physics and semiconductor technology.

Figure 2



Schematic of the molecular ordering in the cholesteric and smectic A phases of cholesteryl nonanoate. Figure 3

this and much more was accomplished in pre-history. (See the article by C. S. Smith in *PHYSICS TODAY*, December 1965, page 18).

By the 19th and early 20th centuries new materials were the subject of quantitative experimental studies. Many new insights emerged in this early period, starting from fundamental experiments such as Georg Ohm's finding that different metals had different resistivities, which led to the electronic hypothesis of matter, and, finally, to the free-electron theory of metals of Paul Drude and H. A. Lorentz. Concurrently, the systematics of the geometry and properties of crystals, as given, for example, in the treatises of P. Groth and others, led to the concept that crystals were composed of stacked arrays of atoms. Pierre Curie discovered how different magnetic materials behaved; Paul Langevin and Pierre Weiss used statistical mechanics and mean-field theory to develop classical models.

It is only in the past 50 years however, that we have learned in microscopic detail about the structural defects that make metals ductile, the energy-band structure that makes gold gold, glass transparent and so on. Probably more knowledge of real solids has been accumulated in the past 50 years than in all the previous years. Increase in our knowledge of materials and our ability to manipulate them is now measured in years rather than millennia. This assertion contrasts with Thornton Read's somewhat wistful comment in his informative article (in

PHYSICS TODAY, November 1953, page 10). "It is one of the discouraging features of working on dislocations that centuries of empirical metallurgy have uncovered practical results whose discovery would otherwise have been the worldly reward of pure science. In this respect dislocation theory is less fortunate than nuclear theory and semiconductor electronics."

Read was writing at the time when the understanding of slip and fracture on an atomic basis had just caught up with empirical practice. The idea of dislocations, introduced into physics by G. I. Taylor in the 1930s, had just been experimentally confirmed. Conyers Herring and John Galt had, using 1-micron-diameter tin single-crystal whiskers, found the roughly thousandfold increase in strength predicted for dislocation-free metal. F. C. Frank had just pointed out the unique role of the screw dislocation in promoting single-crystal growth. The significant advances flowing from this increased understanding soon materialized, and they continue to do so at such a rate that I'm sure Read would, today, feel very differently.

The emergence of solid-state physics

Solid-state physics began as an identifiable field of physics when William H. Bragg constructed an x-ray spectrometer shortly after the discovery of x-ray crystal diffraction by Max von Laue, W. Friedrich and P. Knipping in 1912. With ever increasing capability, x rays

have continued to be used to probe the structure and dynamics of solids. Today synchrotron radiation from storage rings (see the special issue of *PHYSICS TODAY* in May 1981) is used for powerful new x-ray sources, allowing the study of phenomena involving relatively few scattering centers, such as ordering in two-dimensional systems.

During the early 20th century the successes of solid-state physics included the explanation by Einstein—and the refinements by Peter Debye, and Max Born and Theodore Von Kármán—of the fall-off of specific heat at low temperatures; this fall-off had been discovered after the liquefaction of hydrogen by James Dewar and helium by Heike Kamerlingh Onnes. Solid-state physics really came of age after Wolfgang Pauli discovered in 1926 that Fermi statistics are a necessary ingredient in metal physics. By 1933 the quantum theory of solids had been developed through the work of Hans A. Bethe, Felix Bloch, Nevil F. Mott, Rudolf E. Peierls, Arnold Sommerfeld, A. H. Wilson, and others. A good account¹ of this heroic period is given by Lillian H. Hoddeson and Gordon Baym.

Few quantitative *a priori* calculations of materials properties existed before World War II, primarily because good control of materials preparation had not yet been achieved. For example, transport measurements did not yield intrinsic properties. There were some notable successes, however. One was the explanation by Peierls of the diamagnetic oscillations ob-

served by W. J. de Haas and F. M. van Alphen in single-crystal bismuth as a function of applied field. Another was the direct observation by x-ray emission and absorption experiments of bands of allowed energy states that had been predicted for electrons in metals.

There were serious doubts, however, as to the wide applicability of the theory to real solids. Interactions between electrons in metals (that is, correlation effects) were not treated beyond mean field theory and the exclusion principle. Even after the War, W. F. Giaque, in whose laboratory I worked, was convinced that the lack of an adequate method for handling electron-electron and electron-ion interactions made the theory unreliable. The development of some of the physics and formalism needed to understand the complex many-body problem, with 10^{22} degrees of freedom, is discussed by Pines in this issue of PHYSICS TODAY. If periodicity were an essential feature of all the models, why was there so little difference between the electrical conductivity of liquid and solid metals? The answer lies in the fact that the effective scattering potential, the pseudopotential, is weak.

Giaque, along with some others, was ahead of his time in recognizing the importance of using well-characterized single crystals. I found this out during my first years of graduate school, when I spent most of my time growing large crystals, following methods worked out by Alan Holden. My

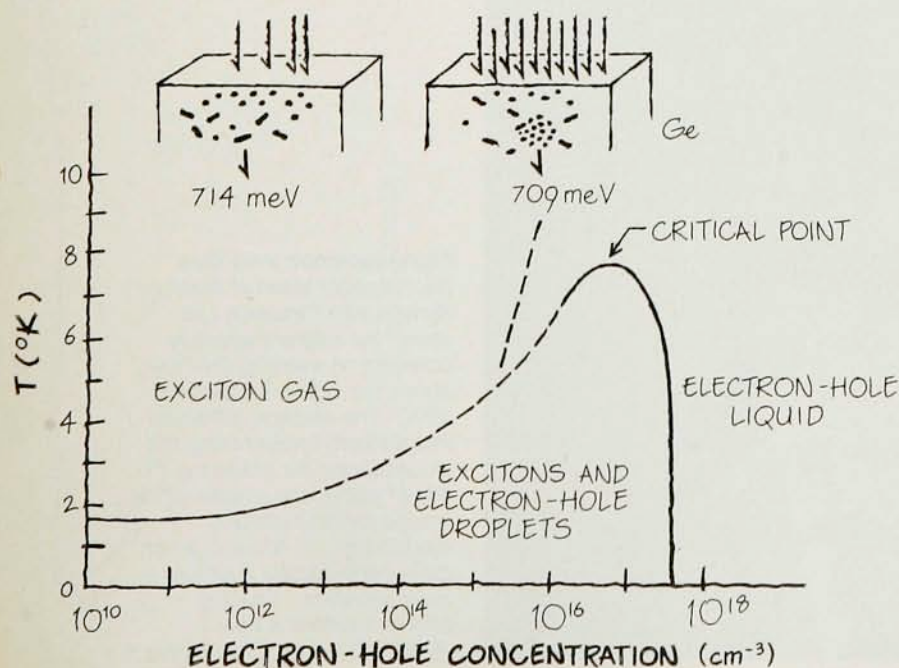
goal was to study magnetic ordering in ellipsoidal specimens of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$. Later others grew metallic single crystals of high purity, making it possible to take advantage of techniques such as cyclotron resonance, magnetoresistance, the anomalous skin effect, and oscillatory magnetic-field effects to map out Fermi surfaces—first of simple metals and finally of the transition metals.

The most consequential and dramatic employment of high-purity single crystals was in the invention of the transistor, by John Bardeen, Walter Brattain and William Shockley. The enormity of the events of 1947–48 does not seem to have been widely appreciated; the modest press coverage (see figure 1) contrasts sharply with some of today's reporting. Once high-quality semiconductors became available and long-lived minority carriers—electrons or holes—were found experimentally, a whole new subfield of semiconductor physics erupted. The most noteworthy early success was the ability to predict and then to prepare an ideal p-n junction by overcompensating an arsenic-doped single crystal of germanium with gallium while the crystal was being pulled from the melt. The rectifying behavior was in quantitative agreement with Shockley's theory. The new physics quickly formed the basis of a new solid-state technology that today has grown to a multi-billion dollar world industry in silicon chips alone and has affected the lives of just about everyone. The growth continues almost unabated.

The first generation of solid-state physicists in this country was educated at a few universities in this country, notably Princeton and MIT. The second generation grew at Bell Laboratories, General Electric, Purdue and a few other centers; then a broad diffusion back into universities and industry followed. As the solid-state technology expanded in the 1960s, most of the educational responsibility for the technology and much of the connected research was taken over by electrical engineering departments.

However, the technology continues to make new demands upon physics. The transistor revolution has, accordingly, resulted in a substantial increase in the funding available for all kinds of solid-state research, as well as the development of sophisticated research tools and materials. A sampling of the very effective two-way interactions between physics and technology is given in figure 2. In silicon technology, the rapidly increasing number of elements per chip and consequent increase in performance has been made possible by a corresponding scaling down in the size of each element. Surface physics has gained new importance and vitality. An approximately thousandfold decrease in size and in power consumption occurred when circuits with vacuum tubes were replaced by transistors. In the past two decades another factor of 10^3 in power and an even larger relative reduction in size has occurred as large-scale integrated circuits have been built onto silicon chips. One or two orders of magnitude further reduction is still expected before the ultimate limits are reached. An entirely new technology of digital superconducting electronics may then take over.

Concurrently with the transistor revolution, what might be termed a "resonance revolution," occurred when the techniques of rf and microwave generation and detection, mastered during World War II,



Phase diagram for electrons and holes in pure germanium. The density of excitons is probed by monitoring their infrared luminescence at 714 meV. Electron-hole droplets are associated with luminescence at 709 meV.

Figure 4

were applied to solids. The many solid-state resonances that were soon discovered, such as nuclear magnetic, electron paramagnetic, cyclotron, ferro- and antiferromagnetic, gave quantitative determinations of energy levels, crystal field splittings, hyperfine fields and relaxation processes.

Some topics of current interest

One day in 1955, while I was driving between Murray Hill and Princeton with John Bardeen and Bernd Matthias, the question "what is the most important unsolved problem in solid state?" was raised. After a pause not untypical of one of my two companions, John replied, "I can think of two: superconductivity and the resistance minimum." These two phenomena, which require only a simple circuit and a sample in a variable temperature environment to measure, turned out to require the discovery of ingenious theoretical methods before they could be understood. As Bardeen foresaw, both phenomena had a major impact on physics; one involves condensation into a macroscopic quantum state with spectacular physical properties and technological possibilities; the other is caused by the combination of phonon scattering, which de-

creases as the temperature is lowered, and the "Kondo" or spin-dependent scattering, which increases and eventually saturates. The pairing Hamiltonian introduced to establish the superconducting ground state and the successful application of renormalization techniques to solve the Kondo problem have influenced developments in nuclear and particle physics.

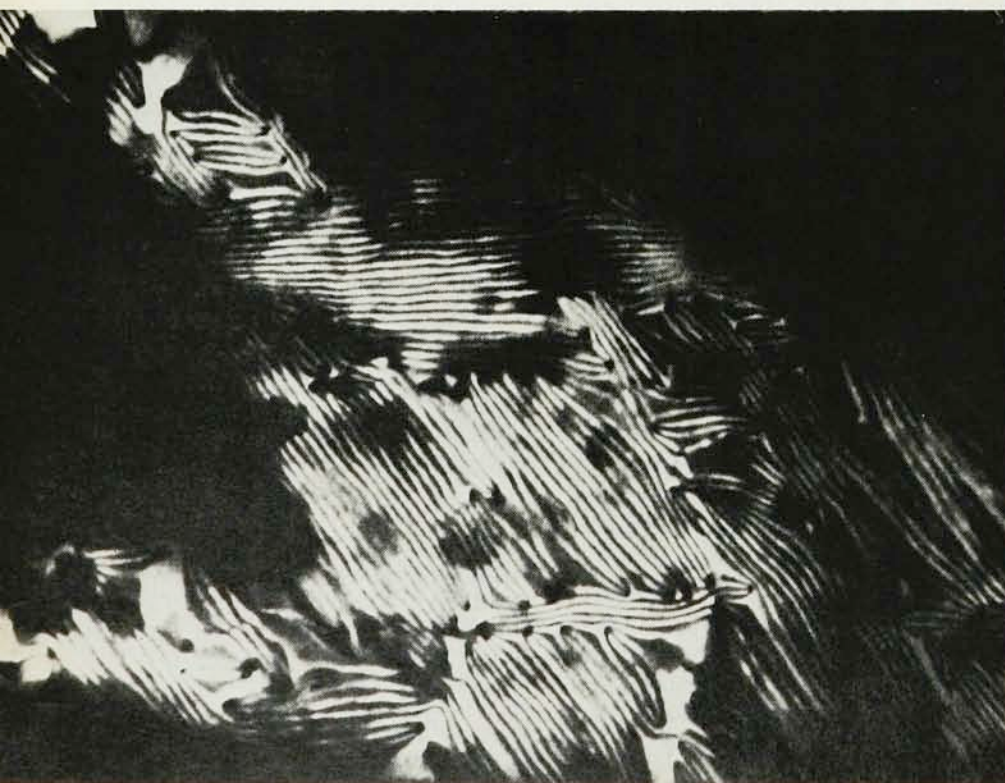
Today there are many unanswered questions, and, perhaps even relatively tougher ones. Is there a minimum metallic conductivity at $T = 0$? How do various ground states compete with each other? How does one describe states far from equilibrium? What is the highest superconducting transition temperature and the related question, is there superconducting pairing other than via the exchange of virtual phonons? What are the atomic relaxation or reconstruction processes that take place at surfaces and interfaces? What are appropriate ways of bridging the region between atomic physics (with, say, fewer than 10^2 particles), and solid-state physics (with more than 10^6 particles).

Good progress is being made in answering these questions and others that I have neglected to mention and that perhaps by the 75th anniversary of the AIP may well have turned out to be the

most important ones.

The issues of *Physical Review B* and comparable journals are loaded with research in which external probes (lasers, x rays, electrons, neutrons, ions, Mössbauer nuclei, and more recently ballistic phonons) as well as thermodynamic quantities (heat capacity, dielectric and magnetic susceptibilities, elastic moduli) are used to determine the properties of a wide variety of well characterized compounds. The characterization often leads to information on diffusion, radiation damage, and other atomic properties. Powerful methods of calculating energy-band structures using pseudopotentials, augmented plane waves and interpolation schemes are applied to the same compounds. Calculations of the total energy of solids are now accurate enough to give structural and elastic properties that are within a few percent of the measured quantities. The agreement implies that the local-density formulation used to describe the many-body exchange and correlation effects is highly accurate for ground-state problems.

In the next sections I have picked out representative areas to illustrate some important and exciting progress being made. Naturally, such a selection reflects personal experience and bias: I apologize for not including other equally significant work.



High-resolution x-ray data (facing page) taken at Stanford Synchrotron Research Lab show² the different structure obtained on warming 2H-TaSe₂ above the lock-in transition at 90 K. The electron diffraction images (left) formed using the incommensurate scattering show³ real-space images of the striped electron-density modulation. In addition, a rich defect and domain structure is clearly evident. Spacing between stripes is about 400 Å.

Figure 5

Phase transitions

Transitions in condensed-matter systems occur as a function of temperature, pressure, stress, field, or other parameter. As new ranges become available, new transitions are discovered. Today temperatures as low as 10^{-3} K, pressure ranges between 10^5 and 10^6 atmospheres, magnetic fields up to 20 tesla (or, pulsed to 50 tesla) are commonly available for quantitative undertakings, and more extreme conditions can be qualitatively explored. Unexpected and occasionally spectacular effects are found when microscopic entities interact cooperatively. Weak first-order or second-order transitions occur that have universal characteristics, whether they be magnetic, superconducting, superfluid, ferroelectric, ferroelastic, incommensurate charge-density or spin-density wave, soft-mode displacive transitions, liquid crystal reorientations, or surface reconstructions. Each transition has a critical point where some symmetry (or symmetries) of the higher-entropy phase is (are) broken continuously. An order parameter, not always obvious, can be found to describe the approach to order of the lower-entropy phase. For example, some organic molecules form liquid crystals that have a "handedness" or chirality. A helical orientation or cholesteric phase can develop, as indicated in figure 3. The centers of mass of the molecules are spatially disordered; the helical order is described by a spiral. When the spi-

ral's period is of the order of the wavelength of visible light, they interact strongly with light, and this makes liquid-crystal displays possible.

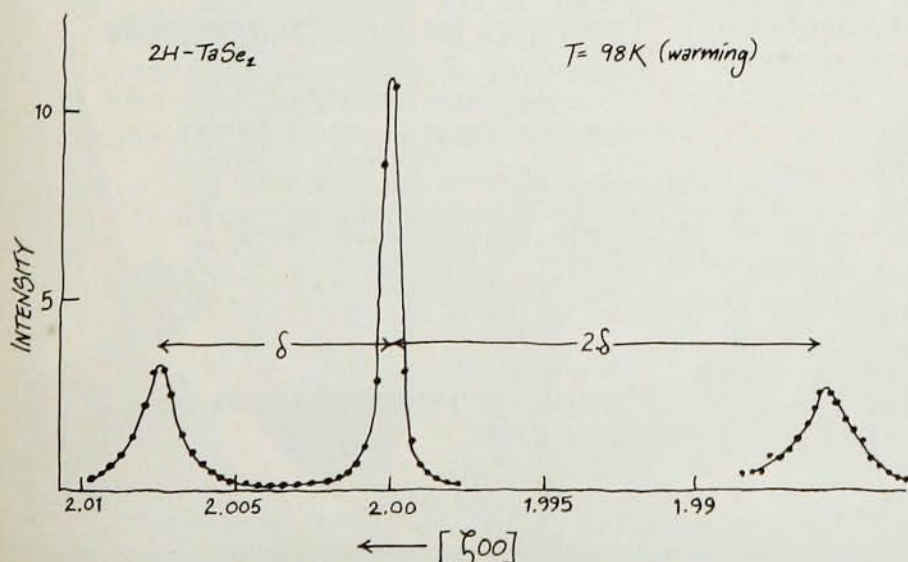
Critical behavior near the transition is believed to exhibit a universal behavior determined by the dimensions needed to describe both the order parameter and the structure. Scaling laws relating the divergence of different properties in the critical region can be measured and compared with theoretical models. Liquid helium-4 has been a most valuable medium for experiment; its purity and good thermal properties make it possible to make quantitative studies to within parts in 10^7 of the superfluid transition temperature. Because of its clean smooth surface, He^4 can also serve as a substrate for studying the crystallization and melting of a monolayer of electrons trapped over its surface. Transitions among nonequilibrium states are of growing interest. A phase diagram showing the condensation of excess concentrations of electron-hole excitons into metallic droplets produced in germanium by optical excitation is shown in figure 4.

Ideal one-dimensional systems cannot have long-range order at finite temperatures. Linear magnetic and superconducting systems frequently do order by weak interchain coupling; a crossover in the effective dimension from one to three occurs. In fact, superconductivity has recently been discovered by a Danish-French group in linear organic charge-transfer crystals (PHYSICS TODAY,

February 1981, page 17). The conducting chains are formed by planar organic molecules stacked on top of each other. Frequently a competitive ordering, first described by Peierls and known by his name, pins the conduction electrons and turns the metal into an insulator as the crystal is cooled. However, in ditetramethyltetraselenafulvalene perchlorate $(\text{TMTSF})_2\text{ClO}_4$ the donor stack remains positively charged and becomes superconducting when cooled, even though another type of instability does in fact occur above the superconducting transition. Several derivative compounds have also been found that under moderate pressure show superconductivity. The roles of exchange, correlation and interchain coupling remain to be sorted out.

When TaSe_2 , an anisotropic layered structure, is cooled below 120 K, a charge-density wave, that is, a spatial periodicity in electron density develops. Its period is determined by a vector spanning the Fermi surface, a vector that bears no simple numerical relationship to the lattice periodicity; the period is incommensurate with the lattice. The mismatch in periodicity, given by δ (see graph in figure 5) decreases² while the amplitude of the wave increases as the crystal is cooled below 120 K. The periods "lock" together, that is, become commensurate at 90 K. The three equivalent directions in the hexagonal structure allow three equivalent charge-density waves to form with domains or regions of "discommensuration" separating regions of constant phase. Upon warming above 90 K, the commensurate-to-incommensurate transition does not occur at the same temperature in all three ostensibly equivalent directions. The intermediate phase consists³ of striped regions (see photo in figure 5) containing two incommensurate and one commensurate charge-density waves.

Different kinds of instabilities can coexist, leading to competition between the different ground states. NbSe_2 and TaS_2 , closely related to TaSe_2 , undergo weak charge-density wave transitions followed at lower temperatures by a superconducting transition. Reactions that insert insulating organic bases between the conducting 6-Å TaS_2 layers and separate them by as much as 50 Å, destroy the charge-density waves with



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consequent increase in superconductivity. Competition between magnetism and superconductivity has been found in perhaps at least ten other ternary systems in which the magnetic rare-earth atoms on one set of sites interact and order. If the order is antiferromagnetic it can coexist with the superconductivity. As the temperature is lowered, the compounds $\text{Ho-Mo}_6\text{S}_8$ and ErRh_4B_4 first become superconducting and then, with further cooling, the rare-earth magnetic moments condense into a long-range spiral structure that coexists with the superconductivity. At still lower temperatures the rare-earth alignment becomes ferromagnetic and destroys the superconducting state. The compounds have both upper and lower superconducting transition temperatures.

Materials science

In most cases quantum liquids and solids such as condensed helium are not available; consequently materials research plays an important role in producing new systems that can expose new physics and can test models. Because materials frequently have structural characteristics that determine their behavior, one can modify the structure and relate

that modification to an observed change in behavior. The periodic table, useful in predicting the existence of elements in the 19th century, continues to be useful in the 20th. Considerable research may be required before compounds can be obtained in a form pure enough to study the predicted intrinsic properties. By the periodic-table approach H. Welker in Germany was able to show that highly purified III-V compounds are semiconductors related to germanium and silicon. This observation has led to a wealth of new physics, new semiconductors and new devices such as light-emitting diodes and solid-state lasers. Figure 6 shows the participants in the discovery of another III-V compound, cubic BN, which, as predicted by averaging over the periodic table, rivals diamond in hardness. The periodic table has also been used as a guide for discovering many new superconductors, by Matthias and others. Superconductivity, once considered a rare phenomenon, is the commonly found ground state for metals.

While there are only 230 spatial arrangements possible for monatomic periodic lattices, the number of ways to arrange atoms in an amorphous solid is infinite. So it is a real challenge to discover actual structures, local order and the effects of impurities and imperfec-

tions. Conceptually as well as experimentally, an amorphous solid or a glass can be obtained from the crystalline state by increasing the degree of disorder, from the liquid state by quenching, and from the vapor state by condensation of either atoms or small molecular aggregates. The achievement of technologically attractive properties—transparency, strength, non-corrosiveness, isotropic response, resistivity (highly insulating, semiconducting, or metallic) and simplicity of synthesis, depend upon a fundamental understanding. For example, the knowledge of infrared vibrational spectra and crystal-field states obtained from optical absorption experiments and spin resonance over the past three decades was important when it became necessary to produce more transparent glass for fiber-optics communication. The thousandfold increase in transparency since 1970 (figure 7) came from being able to identify and then to reduce the trace amounts of absorbing centers and, in addition, from being able to reduce the Rayleigh scattering by a modified chemical-vapor deposition process.

The discovery (1960) that metals as well as oxides and chalcogenides can be quenched into an amorphous state has opened the way to entirely new classes of glasses. Amorphous semiconductors have also been actively studied. Hydrogen has been found to compensate electron traps in amorphous silicon and make it possible to "depin" the Fermi level and to add electrically active donors and acceptors.

Transport

In 1958 Philip Anderson raised fundamental questions about the distinction between a metal and an insulator (at $T = 0$), predicting that when the degree of disorder exceeds a critical value, conduction-band states will be localized.

Participants in discovery
of cubic BN are shown in this 1957 photograph. From left: Percy Bridgman, Herbert Strong, Robert Wentorf and Irving Langmuir. General Electric Research Lab photo courtesy AIP Niels Bohr Library.

Figure 6



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There has been much recent activity exploring the consequences. Evidence supports the prediction that in one dimension localization will occur at $T = 0$, providing the resistance is greater than $2h/e^2$ or about 8000 ohms. The localization distance and temperature are experimentally unrealizable for macroscopic copper wire because the conditions require negligible inelastic scattering over a length corresponding to greater than about 8000 ohms. Localization has been established in wires with very small cross-sectional area and in two-dimensional field-effect transistors (MOSFETS). In three dimensions, experiments in some disordered alloys such as Au-Ge indicate that the onset of conduction may be continuous at $T = 0$; that is, there is no minimum conductivity. Discontinuous metal-insulator transitions are frequently found, however, as predicted by Mott on the basis of electron-electron correlations.

Charge transport itself is very anisotropic in systems with fewer than three dimensions; other unusual characteristics are possible too. In NbSe_3 and related "chain compounds," an instability driven by a spanning vector of the almost one-dimensional Fermi surface causes the charge density to become periodic. The charge-density wave becomes "pinned" to the lattice by defects and impurities. In NbSe_3 a moderate electric field (about 10 mV/cm) can depin the charge-density wave or cause it to tunnel. Charge is then transported by the sliding charge-density wave. There is also a theory and some evidence to support the idea that charge is transported in polyacetylene chains by moving defect regions, or solitons, along the chains. In one-dimensional chains with $1/3$ filled bands the theory predicts that $1/3$ and $2/3$ of an electronic charge can accumulate in the defect regions where the phase of the bond conjugation changes (see PHYSICS TODAY, July 1981, page 19).

Magnetism

The microscopic origins of magnetism in terms of the exchange of localized spins was discovered by Werner Heisenberg; shortly thereafter Bloch showed how conduction-band (itinerant) magnetism could arise from the same interac-

tions. At the time of Heisenberg's theory the only known magnets were metallic. Later the Philips Eindhoven Laboratory work on oxides with the spinel structure (magnetite) showed that they were intrinsically insulating and also that the magnetic and electric properties could be controlled by relatively straightforward chemistry. Subsequently, the magnetic interactions could be understood in terms of "superexchange" through the oxygen ions. An important class of magnetic insulators became available for radio frequency and microwave inductors and non-reciprocal devices.

A new class of exceptionally strong permanent magnets based upon rare earth-cobalt compounds and alloys, for example CeCo_5 , has recently become available. Highly anisotropic behavior results from the ordering, which involves both localized 4f electrons and itinerant 3d electrons. In processing, the microstructures of the active magnetic compound must be kept small enough to be a single domain to prevent magnetic reversal by domain-wall nucleation, which would destroy the strong external magnetic field.

Until the 1970s the only known magnetic materials were crystalline (at least one unrecognized amorphous magnetic material existed), although no theorem required spatial periodicity for the occurrence of magnetic order. Amorphous or glassy magnetic metals were discovered almost as soon as we learned how to make glassy metals. The lack of crystallinity offers the possibility of very little anisotropy and hysteresis. These characteristics are important for transformers in the power industry.

Perhaps the most demanding requirements for new magnetic materials come from the computer industry. The ability to address memory, to read and to write with increasingly rapid times calls for information bits of ever decreasing size. These bits can be domains of differing polarization, which form as a result of competition between the energy of the magnetostatic field external to a sample and the internal interactions. The domains are separated by walls whose free energy is dominated by uniaxial anisotropy and exchange. These latter factors can be controlled by chemical substitution on certain lattice sites. In

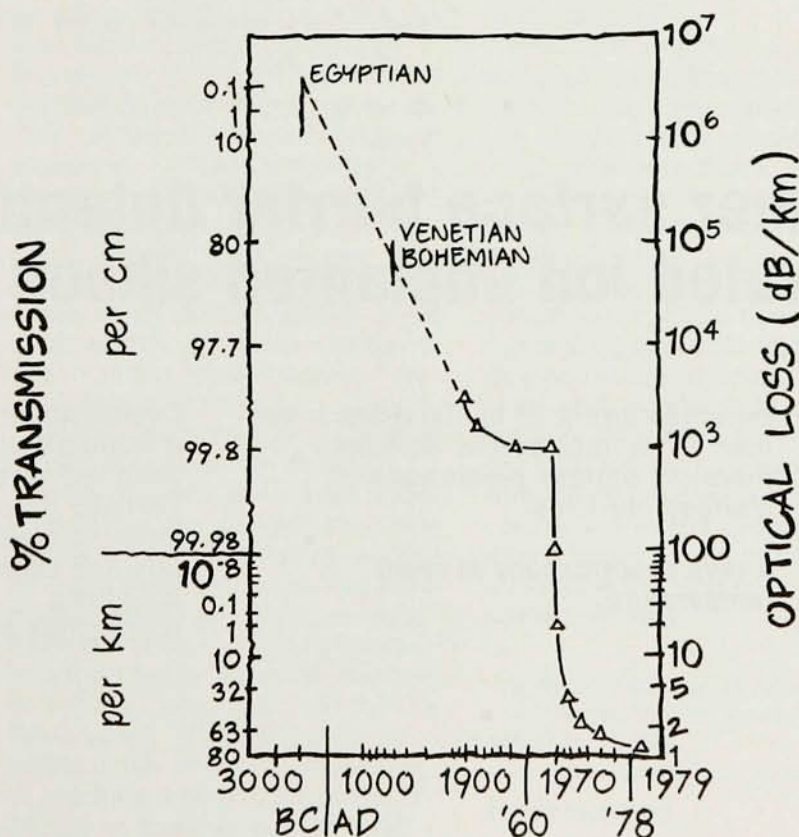
magnetic garnet structures (which are oxides containing 3d and 4f ions) small cylindrical domains with reversed magnetization can be stabilized. The cylinder axis is perpendicular to the sheet; so the domain appears as a bubble. The bubbles are mobile and respond rapidly to weak signals. They are being used as bits and serve as rapid-access high-density (bubble) memories.

Superconductivity and superfluidity

In 1956 John Bardeen, Leon Cooper and J. Robert Schrieffer discovered the microscopic basis of superconductivity: Conduction electrons with equal and opposite momenta and spins form pairs that condense into a superconducting state. The energy gap that separates the superconducting ground state from excited states has been measured by heat capacity, acoustic and optic absorption and directly by electron tunneling. Experimenters established that the attractive interaction giving rise to

the pairing is phonon-mediated when they found that the transition temperature into the superconducting state, T_c , is dependent upon isotopic mass. A wealth of information about the electron-phonon mechanism has been obtained from single-particle (Giaever) tunneling measurements and the strong-coupling extension of BCS theory. The microscopic parameters entering the theory can all be obtained from normal-state properties. In practice, however, the superconducting behavior is used to determine the normal-state properties.

All known superconductors so far have been found to pair via exchange of virtual phonons, although other exotic models have been proposed; these involve pairing via the exchange of other quasiparticles (usually with much higher energy and consequently with predictions of much higher T_c). Empirical evidence to date indicates that when the electron-phonon interaction becomes too great, as when some parameter such as composition is varied, a structural instability sets in and a

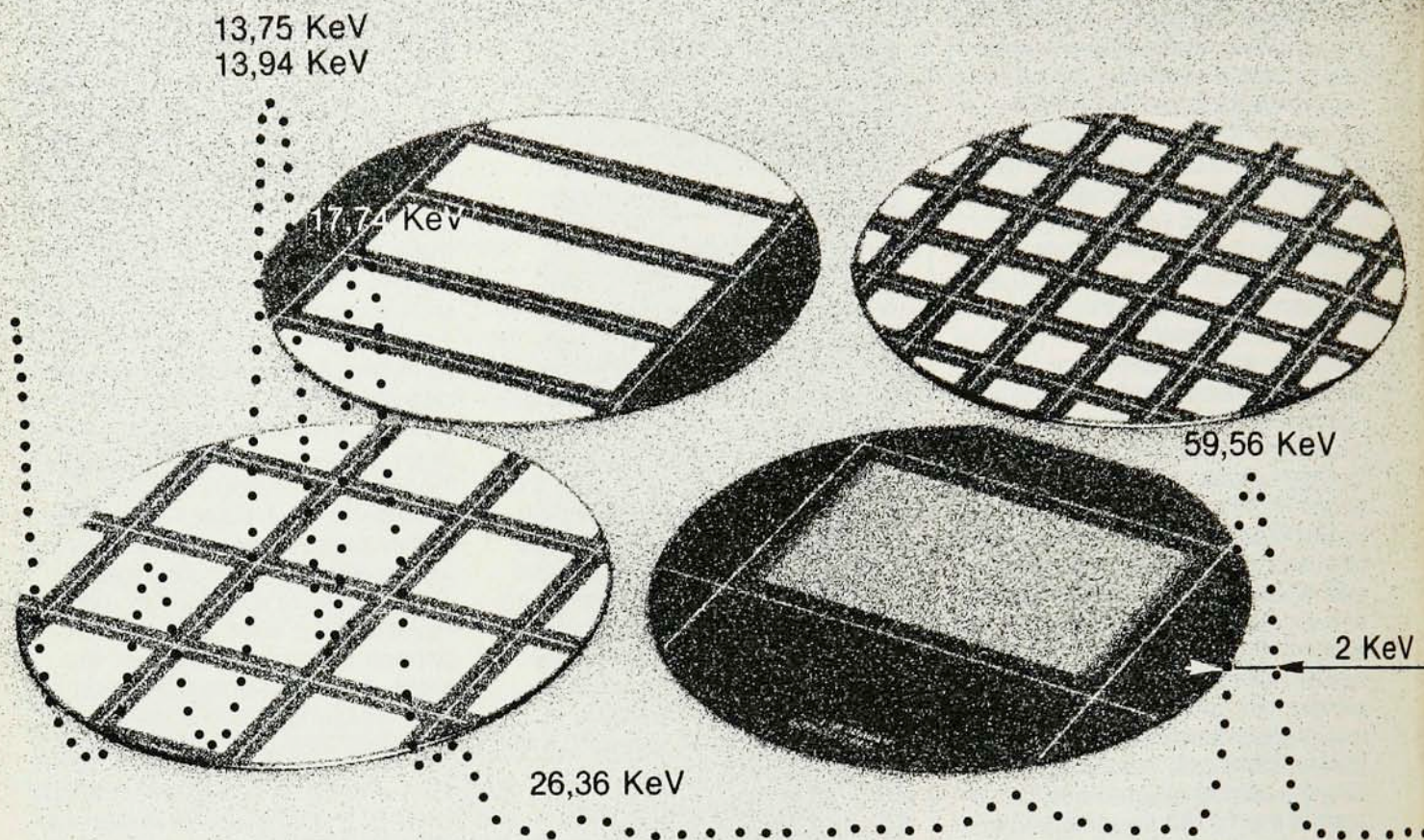


Optical transparency of glass
improved by more factors in the decade of the 1970s than in the preceding 1000 years. The demands of technology often result in major performance improvements when the physics of the underlying phenomena is understood.

Figure 7

nuclear spectrometry :

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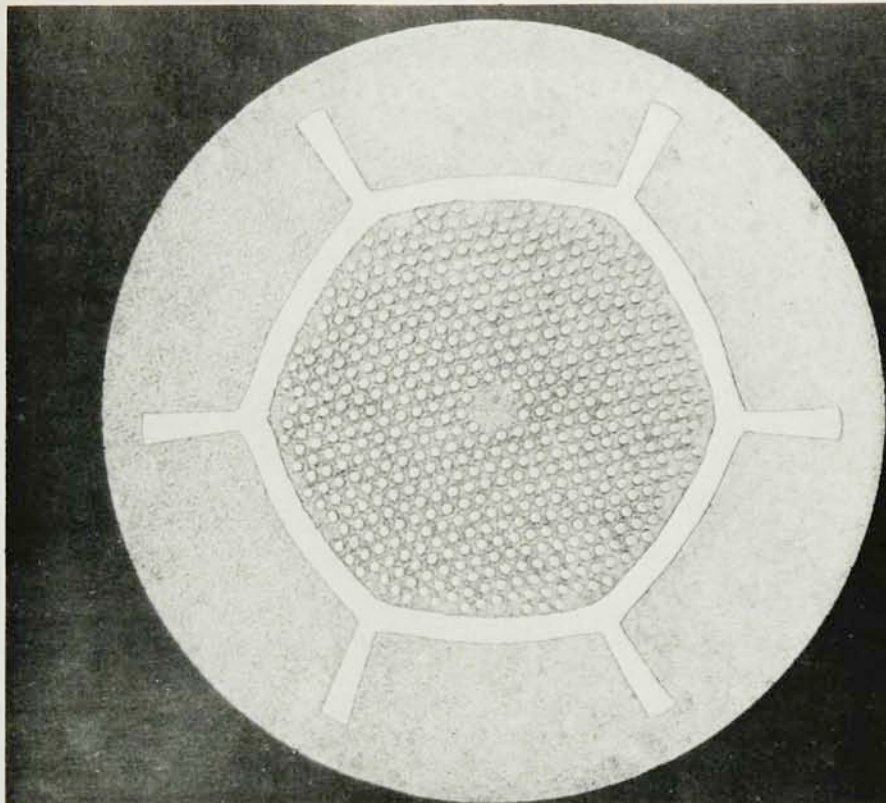


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Prototype multifilamentary NbTi superconducting wire for use in Los Alamos 20-MJ tokamak ohmic-heating coil. The 2.04-mm-diameter wire shown in cross section contains 540 NbTi alloy filaments, each 32 microns in diameter. The conductor used in the coil is a 216-strand cable with a total critical current of 90 000 amps at 7.5 T. It can be pulsed from +7.5 to -7.5 T in 1 sec; the Cu-Ni shell-and-fins are needed to reduce eddy-current loss in pulsed operation. Photo courtesy of Intermagnetics General.

Figure 8



new, less-superconducting phase is formed. The compounds with the highest known T_c 's (19 to 23 K) all have the same crystal structure (the cubic A15 structure) and are all metastable. To increase T_c further it would seem to be necessary to increase metastability, unless of course some new mechanism is discovered.

Each superconducting pair is characterized by an amplitude and a phase; the ground-state wave function is a coherent superposition of pairs—all with the same phase. One consequence of the single-valuedness is the quantization of flux. The quanta, although small, are macroscopic; they were first found by measuring discontinuities in the magnitude of the magnetic field trapped in a capillary tube. Flux quanta play an important role in superconducting devices, both large and small. In the high fields and large currents that exist in large devices, the flux quanta can be bound at pinning sites, that is, free-energy minima. The pinning resists the strong Lorentz forces, which are necessarily present, and prevents dissipation. An example of a modern cable for high-current, high-field use is shown in figure 8.

In Josephson and other small devices, a weak link such as a thin oxide barrier exists, across which the phase can change, and across which superconducting pairs can tunnel. A phase difference $\Delta\phi$ drives a superconducting current $I_0 \sin\Delta\phi$ (the dc Josephson current). In a magnetic field, the flux-quantization condition gives rise to interference, which makes the total current periodic in field. In superconducting quantum interference devices (SQUIDS), the flux is controlled by an external circuit; SQUIDS are the most sensitive known detectors of magnetic fields. When the current exceeds

I_0 , the device switches to a state of finite voltage in which single-particle tunneling occurs. The energy required to switch is about four orders of magnitude less than the best semiconductor bipolar device. When an external voltage is applied to a Josephson junction the change in phase increases linearly, leading to oscillations in supercurrent with a frequency $\omega = 2eV/\hbar$. This ac Josephson effect, which permits voltage to be measured by a frequency determination, is the present basis of the US legal standard volt.

Much understanding of quantum fluids has recently come about from studies of helium-3, as is discussed in some detail in the article by Pines. Liquid helium-3 is a Fermi liquid that condenses into a superfluid state near 2 mK, roughly three decades lower in temperature than typical superconductors, or for that matter than helium-4 (a Bose liquid). The hard-core potential in He^3 would be expected to preclude s-type (opposite spin) pairing as found in superconductivity and, in fact, experimental evidence has been found for p-type pairing. Three different superfluid phases exist, depending upon temperature, pressure and magnetic fields. A story of some of their remarkable superfluid proper-

ties was recently told by David Mermin in *PHYSICS TODAY*, April 1981, page 46.

Are there any more condensed superfluid systems remaining to be found? The answer appears to be yes. Experiments are underway in which polarized, atomic hydrogen is condensed onto a substrate at liquid-helium temperature. When the density of the aligned atomic hydrogen becomes great enough, condensation into a new superfluid Fermi state is predicted. Whether its macroscopic properties turn out to be as spectacular as superconductivity remains to be seen. But the reaching out far beyond equilibrium into unknown states that condensed-matter physicists are attempting is bound to bring new understanding, and perhaps even some surprises.

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