CRYSTALS

To probe a crystal one can use neutrons, x rays, electrons and now, protons. But crystallographers are scrutinizing the accuracy of their measurements. Improvements in crystal growing are leading to new solid-state research, and huge biological molecules are being unravelled crystallographically.

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with contributions by CHARLES S. BARRETT and DAVID HARKER

THE CONCERN of modern crystallography is with the atomic theory of matter in all states of aggregation and with the optical principles of the diffraction of short-wavelength radiation by such matter. This broad definition is a far cry from the morphological emphasis of early classical crystallography; it is, however, just a logical extension of concepts initiated by Max von Laue's demonstration in 1912 of x-ray diffraction by crystals. Not only can the physical properties of a crystal be interesting; they can also be esthetically pleasing (figure 1).

Modern techniques now enable the complete x-ray or neutron pattern scattered by single crystals to be measured under automatic control. X-rays scattered by liquids, or electrons diffracted by gases, are being similarly measured. These patterns may be analyzed with a combination of powerful theoretical and computational tools that are still rapidly evolving. Difficulties often arise in the analysis that require the information contained in the diffraction patterns to be interpreted on a highly individual basis. Nevertheless the structural crystallographer is increasingly shifting his emphasis from problems contained within the technique to attempts at correlating the physical and chemical properties of the material studied with the atomic arrangement he has deduced. The physical crystallographer, on the other hand, is acutely aware of the limitations in present diffraction models and is striving to improve them as well as to extend the optical principles that underlie the models.

Two new diffraction phenomena are being used: proton scattering, and low-energy electron diffraction by magnetically ordered surface arrays. Previously diffractionists confined themselves to the interaction of x rays, neutrons and electrons with matter. The accuracy with which diffracted x-ray and neutron intensities can be measured has recently come under rigorous scrutiny; the validity of derived structural information depends on accurate intensity measurement.

Phase transitions, especially the onset of coöperative phenomena, are being studied by new crystallographic techniques. The problem of how well an individual crystal specimen represents the intrinsic properties of the material is receiving increasing recognition. Much solid-state physics depends on the supply of single crystals. The crystal growers have recently been successful in producing many new interesting materials, and new understanding of crystal growing is coming from simulation experiments like the one shown in figure 2. X-ray diffraction techniques are being applied to numerous complex biological molecules.

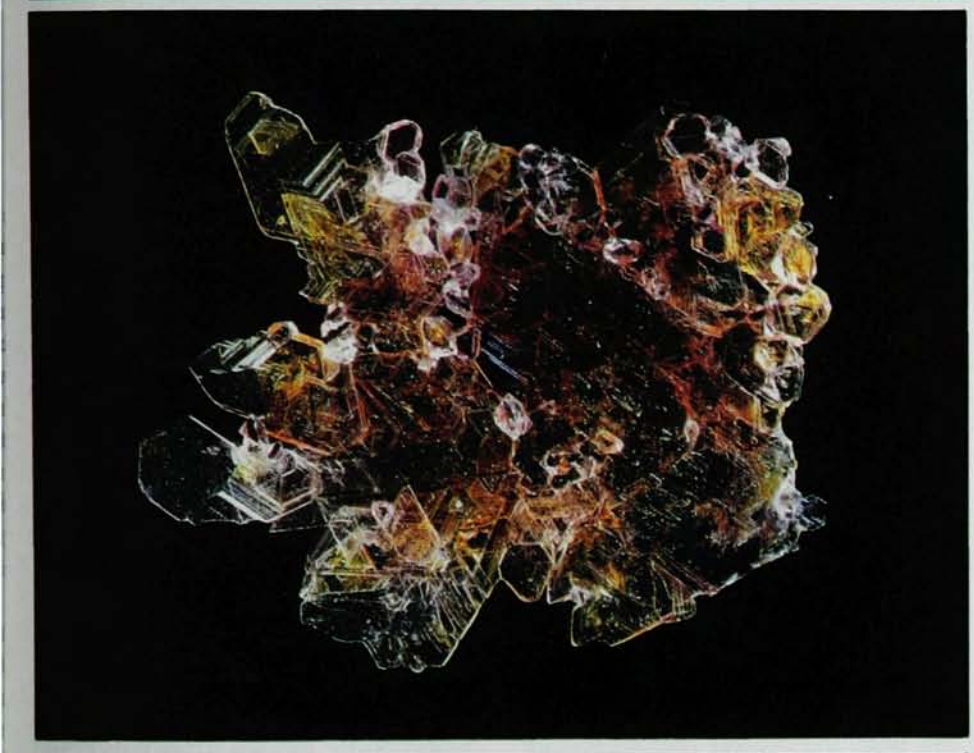
Many of these rapidly moving fields will be discussed at the VIII International Congress of the International Union of Crystallography (page 23).

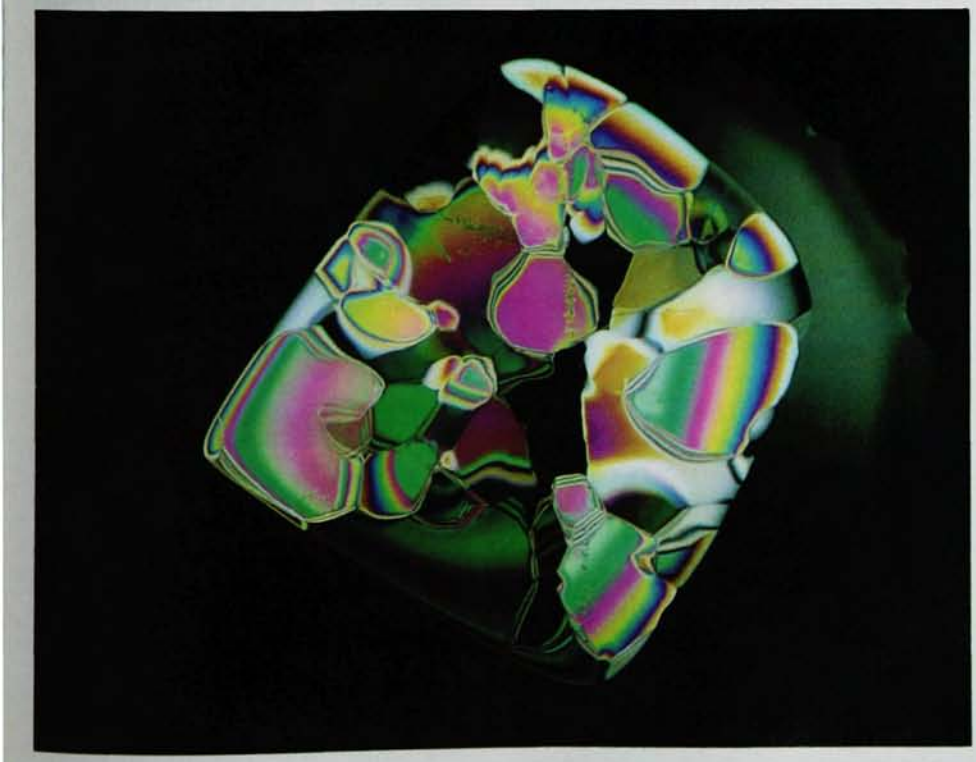
Proton and electron scattering

Two scattering techniques, each of which may develop into exciting new fields, have recently made their appearance. Proton scattering, using energies less than 150 keV, produces very detailed patterns containing considerable crystallographic information about the surface layers of the scattering material. The necessary theory required to relate the intensity of the various parts of the proton scattering pattern to the structure of the surface has still to be fully established. An account of this technique is given by Charles S. Barrett, a leader in the field, in the box on page 33.

The diffraction of electrons with energy less than a few hundred volts has been widely used in the last decade for studying the structure of crystal surfaces. Recently, Richard Stern (Polytechnic Institute of Brooklyn) showed that electrons with energies greater than about 75 eV are scattered not only by the surface structure, but also by the triply periodic structure of the bulk crystal. An excellent account of the status of low-energy electron diffraction last year is given in volume 4 of the *Transactions of the American Crystallographic Association* (available from Polycrystal Book Service, PO Box 11567, Pittsburgh, Pa. 15238).

In a new application of low-energy electron diffraction, coherent scattering from an ordered magnetic spin array has been observed by P. W. Palmberg, Roger DeWames and Lawrence Vredevoe[1] (North American Rockwell Corp). With this technique they could do magnetic scattering without the expense of a large neutron source. They showed that fractional-order reflections diffracted from the





CRYSTALS. Top photo is pink ruby (Al_2O_3 containing chromium) grown from the flux (lead oxide and boron oxide) showing rhombohedral growth steps and flux inclusions. Middle photo shows spontaneously nucleated ruby crystals exhibiting two habits; they were grown like the crystal at top but temperature was higher. (Ruby grown by J. P. Remeika.) Bottom photo is section of ice cube about 2 mm thick, that is viewed between crossed polarizers. (From R.L. Barnes.) —FIG. 1

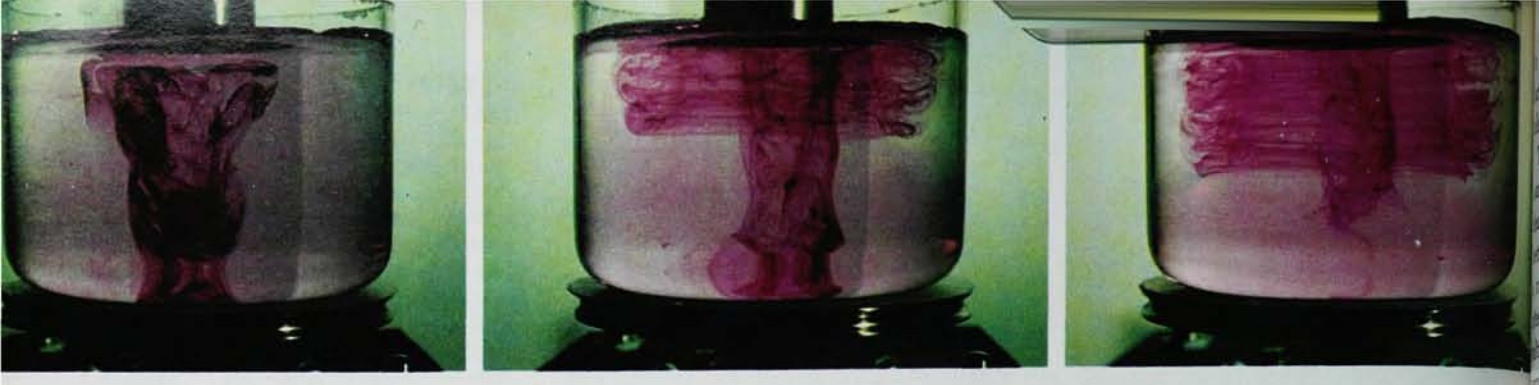
clean surface of an antiferromagnet appear reproducibly as the crystal temperature is lowered below the Néel point T_N (magnetic ordering temperature) and disappear again as the temperature is raised above T_N (figure 3). The most probable origin of this scattering is the exchange interaction between the incident electrons and the ordered array of magnetic electrons. The intensity of these fractional-order reflections (about two percent that of the nonmagnetic reflections) agrees well with the intensity expected for exchange scattering.

Low-energy electron diffraction by exchange interaction should provide a particularly sensitive probe for magnetic lattice arrays with a periodicity not commensurate with that of the atomic array, as is typical for many planes within an antiferromagnet. For planes in which the magnetic ordering is identical to the atomic periodicity, as invariably is found in simple ferromagnets, new reflections will not appear below the ordering temperature. It may be possible to detect changes in the intensity of the diffracted beams below T_N although these changes are generally likely to be small.

Accuracy of intensity measurements

Much experimental crystallography consists of measuring the integrated intensities of the diffracted beams and then correcting for geometrical and other factors to obtain corresponding structure factors for a given material. Error introduced at any point in this process will be propagated throughout the consequent analysis. So one must recognize and determine these errors to establish the validity of derived physical models.

Most attempts to measure integrated x-ray intensities to an accuracy of better than about 10% are now made with diffractometers. Such measure-



CIRCULATION currents in the melt during Czochralski pulling are simulated. Sequence shows dye distributing throughout inner lower cell. Even after long rotation periods, the outer regions, which appear smaller due to optical distortion, remain free of dye. (From reference 3.) —FIG. 2

ments, made manually, are tedious and time consuming. Increasing use is being made of commercially available automatic diffractometers, in which the measurements are typically controlled by instructions on paper tape or cards.

Within the last few years, it has been realized that the error distribution associated with manual or automatic diffractometer data was not fully understood. Although many of the error sources (including those of mechanical and electronic origin in the diffractometer as well as those arising from extinction, absorption, multiple and thermal diffuse scattering, and other crystal effects), have been investigated by a number of laboratories, the overall combination obtained in a normal intensity measurement could only be estimated.

Recently, two multiple-laboratory coöperative experiments have been conducted, one solely within the US, the other internationally, to make the estimate more quantitative. In the first experiment the same crystal was circulated among seven different laboratories, and each measured the integrated intensities of a specified set of reflections. In the second experiment 16 different laboratories each measured a specified set of intensities from a different crystal of the same material, all of which had been prepared in a single crystallization batch.

Analysis of the first coöperative experiments showed that most of the measurement sets contained structure-factor magnitudes that lay within three percent of the probable true values. It was considered unlikely that any of the experimenters measured structure factors to better than about one-percent accuracy. In the second coöperative experiment, the range of disagreement was wider, with most measurement sets lying within six percent of any other and no two sets agreeing closer than three percent.

Each set of measured structure factors from the second coöperative experiment was entered into a least-squares refinement of the structural parameters. The resulting position coordinates suggest that the apparent "standard deviations" are underestimated by a factor of two or three. It is likely that all crystal-structure refinements based on experimental data containing unsuspected or uncorrected systematic error yield standard deviations in position coördinates and thermal parameters that are underestimated.

Improving intensity accuracy

Integrated intensity measurements are generally performed on crystals close to being ideally imperfect in type. These crystals consist of many small blocks of perfect periodicity. Each block is slightly misaligned with respect to the other blocks, forming a mosaic. The highest accuracy one can hope to achieve with these measurements is already obtainable with the method of pendellösung fringes. Norio Kato (Kyoto University) and others have recently used the fringes

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Charles Barrett won his PhD from the University of Chicago. He spent four years at the Naval Research Laboratory, 14 at Carnegie Tech and then returned to Chicago, where he is a research professor at the James Franck Institute. His interests include crystallography at low temperatures, preferred orientations in metals, deformation and transformation of metals, x-ray equipment and methods.

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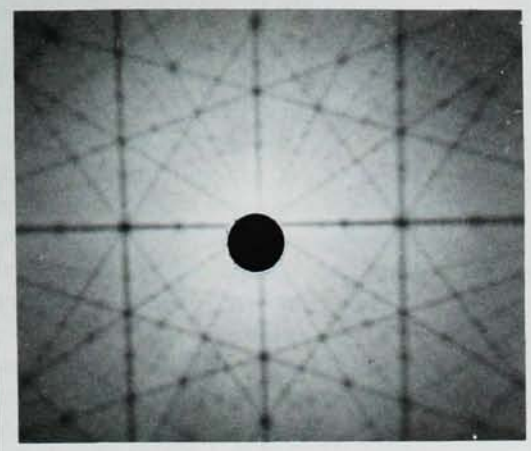
to determine the absolute structure factors of several ideally perfect crystals to one-percent accuracy.

The fringe method depends on dynamical diffraction theory, which deals explicitly with the interaction between incident and Bragg-reflected x rays. When an incident wave excites a single reflected wave, the resulting wave field may be described in terms of two Bloch waves. The mutual interference of overlapping Bloch waves produces pendellösung fringes. By using a flat pencil of incident x rays and a wedge-shaped perfect crystal, one can obtain a section topograph consisting of a set of hyperbolic fringes (figure 4). The absolute value of the structure factor is related to the measured fringe spacing by proportionality terms involving only fundamental constants and a geometrical factor. The difficulty in measuring the geometrical factor reduces the absolute accuracy of the structure factor by an order of magnitude to about one percent. Pendellösung fringes have also been used by Michael Hart (Bristol University) to measure atomic-scattering factors at specific lattice-spacing values with high internal consistency.

Measurement of integrated x-ray intensities with an accuracy approaching one percent, together with comparable accuracy in the calculation of free-atom form factors, leads to many exciting possibilities: At this level one should be able to determine experimentally the charge density in chemical bonds, the density distribution in lone pairs of electrons and the ionicity of the scattering atoms, for example. But to extract such information correctly from the diffraction data, one must have a detailed description of the atomic vibrations.

Considerable progress has recently been made, based largely on neutron-diffraction results, in developing realistic anharmonic vibrational models. Several papers have now appeared in which systematic deviations from the spherical symmetry of free atoms have been demonstrated. As theoretical models for atomic x-ray scattering improve, we can hope to understand the detailed arrangements of electrons in crystals.

No matter how accurately you determine a set of structure factors you cannot use them properly unless the crystal symmetry is correctly determined. The confidence with which assignment of inversion centers is made has recently been considerably increased by the second-harmonic gen-



PROTON - SCATTERING pattern. 100-keV protons are back-scattered from cadmium sulfide crystal. (The film was parallel to the $(11\bar{2}0)$ plane.) A collimated beam from a Cockcroft–Walton accelerator passed through the central hole in the film, fell nearly perpendicularly on crystal surface and scattered back to the film, a distance of 1 cm, in a vacuum chamber. (From W. White and R. M. Mueller, Nuclear-Chicago Corp.)

CRYSTALLOGRAPHY WITH PROTONS

CHARLES S. BARRETT

Any method capable of producing a record of crystal planes and directions that is as detailed as the proton-scattering pattern reproduced on this page is an appropriate subject for research by crystallographers, yet less than a tenth of one per cent of the crystallographers have done any research with protons or other ion beams. On the other hand, starting with the classic paper by Mark Robinson and Ordean Oen of Oak Ridge in 1963, on the ranges of copper atoms injected into copper crystals, there have been many effective experimental and theoretical papers by physicists, with major contributions coming from Denmark, England, Canada, the USSR, and from Oak Ridge, Brookhaven, Argonne and a few other laboratories in the US.

The nature of the interaction of a charged-particle beam with the simplest crystals has been worked out in some detail, and many individual particle trajectories have been computed with fair approximation; ranges are known with considerable accuracy not only in unsymmetrical directions in the simple crystals but also along the directions in which abnormal penetration (channeling) occurs. The back-scattered particles produce patterns that are beautifully filled with crystallographic information.

Why, then, have crystallographers done so little with these patterns? To be sure, the best films and the most effective counter work with scattered particles are done with costly accelerators in the million-volt range. But quite satisfactory patterns can be photographed in minutes using small accelerators in the 25–150-keV range. Probably the main reason for shunning this field is the feeling that little can be learned from such patterns that cannot be learned better and more quickly by x-ray, electron or neutron diffraction. This may, indeed turn out to be true; because the wavelengths of 100-keV protons are about a thousand times shorter than the x-ray wavelengths used in crystallographic research, the angles of reflection are extremely small and many simultaneous reflections occur. With far-from-monochromatic wavelengths and very short coherence distances in the crystal, much overlapping of diffraction effects must be expected.

However, this is not the time to enthrone pessimism. Proton channeling through thin crystals and proton back-scattering ("blocking") patterns are useful methods for determining crystal orientation with speed and precision. Dissolved elements have been identified by the energy spectrum of scattered particles, as well as by the fluorescent x rays excited by the particles, and foreign atoms have been identified as interstitially or substitutionally situated. Few of the possibilities have been exploited for studying the degree of crystallinity, crystal orientations, crystal perfection and identification of phases in the layers within 10–100 nanometers of the surface. As a tool for determining electron distributions and potential distributions in crystals, proton scattering holds promise but is yet to be perfected. As a method for getting definitive information on the structure of crystals (save, perhaps, the elements) the technique is almost untested. Only in this last year have attempts been made to test the possibilities of obtaining crystal structures. At the congress the first attempt to determine atom-position parameters in crystals by scattering patterns is being reported.

Pattern interpretation has been based on elaborate classical computations of individual-particle trajectories. It is now beginning to appear, however, that much simpler calculations than those based on many-beam dynamic diffraction theory may give some useful correlations between crystal structure and the relative intensities in pattern features.

eration technique of Stewart Kurtz (Bell Labs). He has shown that the magnitude of the green second harmonic, generated by an infrared laser beam of 1.064 microns incident on a powder or single crystal, is a highly reliable piezoelectric indicator.

The current situation in the accurate determination of integrated x-ray intensities and structure factors is thoroughly covered in the January 1969 issue of *Acta Crystallographica*, Section A. This issue contains the complete proceedings of an international meeting on this field held last summer in Cambridge, England.

Phase transitions

Phase transitions have long been on the leading edge of solid-state physics. Crystallographic methods can provide detailed descriptions of the state of aggregation within a system before and after the transition. The growing range of pressure and temperature over which diffraction experiments can be made has led to numerous recent crystallographic studies.

As the temperature or pressure of the specimen is varied, a phase transition can be indicated by lattice-constant discontinuities. If a symmetry change occurs, the transition may in addition be revealed by new reflections of a type hitherto forbidden, or by lattice changes that cause line splitting.

Denis McWhan (Bell Labs), for example, led by previously reported anomalies in resistive and magnetic properties, did x-ray diffraction measurements on terbium metal powder (figure 5). Applying high pressure, he observed line splitting in the x-ray pattern. Thus, diffraction patterns given by polycrystalline materials offer convenient means for determination of phase changes, which in turn may elucidate anomalies found in other physical properties as a function of temperature or pressure.

The difficulty with bringing essentially monochromatic x-ray beams out of high-pressure chambers has led to promising nondispersive methods. For a monochromatic incident beam the exit path for diffracted beams must subtend an angle of at least 20 deg at the sample, in order to obtain a useful powder pattern. By using polychromatic x rays or neutrons instead, it is possible to use one or more narrow exit slits at arbitrary but experimentally convenient angles to the incident beam. For x rays, one can analyze the energies diffracted at the fixed angle with a detector such as lithium-drifted germanium coupled to a multichannel analyzer. For neutron studies at high pressures, time-of-flight analysis has been successful. The resulting pattern of x-ray or neutron intensity as a function of scattered energy is entirely analogous to the familiar patterns of intensity as a function of scattering angle and can be similarly analyzed.

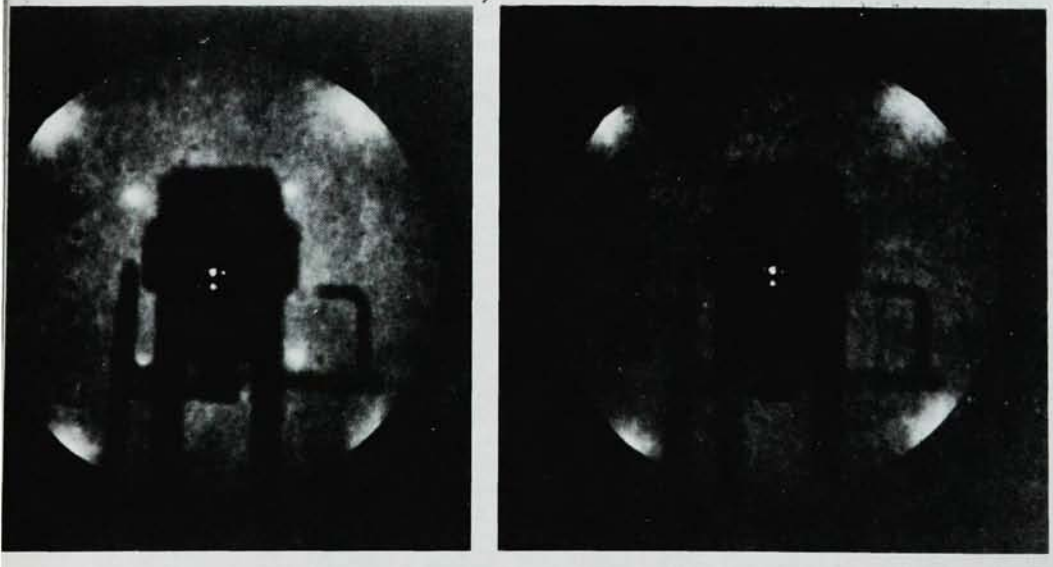
Although determination of structural change at a phase transition is more definitive if a single crystal is used, single-crystal measurements at high pressure are difficult. A few single-crystal transition studies have been made with the material under pressure (in situ). The alternative method, which uses metastably quenched samples, is becoming more common because it is easier. In-situ single-crystal high-pressure work based on nondispersive methods may become useful despite the highly restricted regions of reciprocal space that are accessible to such experiments. Quintin Johnson and his coworkers at Lawrence Radiation Laboratory (Livermore) are developing an interesting new technique, in which a nanosecond x-ray pulse is used to study materials under shock compression. A survey of current diffraction methods and results at high pressures is given in Volume 5 of *Transactions of the American Crystallographic Association*.

Many magnetic transitions in single crystals at liquid-helium temperatures have been extensively studied by neutron diffraction. The beautiful work of Wallace Koehler and his colleagues (at Oak Ridge) on the rare-earth metals clearly demonstrates the power of this experimental method. No other technique could have so unambiguously revealed the nature and relationships of the various helical-spin structures developed by these metals.

Ferroelectric–paraelectric phase transitions are being intensively studied, both for their intrinsic interest and in relation to their electrooptical and nonlinear optical behavior. Several models, of varying complexity, have recently been proposed to relate quantities such as Curie temperature (T_C), spontaneous polarization, and effective atomic charge over a wide group of displacive ferroelectrics. Fundamental to such relations are the quantitative displacements of polar atoms from the positions occupied in the nonpolar state. In many cases high Curie temperatures have made crystallographic measurement on the nonpolar state so difficult that even the symmetry above T_C can only be inferred. Improvements in technique may soon overcome these difficulties.

Real crystals

How well does a given crystal specimen represent the material? Generally, various physical properties are measured on different specimens and correlated later on the assumption that all specimens are probably equivalent.



33-eV ELECTRON-DIFFRACTION PATTERNS from a (100) nickel-oxide surface. In the pattern produced at 400 K (left), one can see the {1/2 0} reflections close to the shadow cast by the crystal-cleaving arrangement. The partially obscured {10} reflections are visible at the edge of the circular field of view. Pattern at right is from same surface at 535 K; {1/2 0} reflections are completely absent. Néel temperature of nickel oxide is 525 K. (From reference 1.) —FIG. 3

PENDELLOSUNG FRINGES in a silicon crystal. More than 30 orders can be seen. Fading above 10th order is caused by use of unpolarized x radiation. This section topograph, enlarged 25 times, was produced by a 10-micron x-ray beam with a wedge-shaped crystal. (From J. R. Patel.) —FIG. 4

Such assumptions may be entirely unjustified. In addition to differences in defect and dislocation distribution, to which many measurements are insensitive, chemical inhomogeneities are likely to be common. Many simple inorganic materials, such as apparently stoichiometric mixed oxides, may exhibit subtle but important differences in their chemical composition and their physical properties not only from one crystal to another, but even within the same single crystal. Thus, Robert Barns (Bell Labs) has found that two $LiTaO_3$ crystals grown from the same proportions of nominally identical starting materials had a difference in T_c of 13°C, with lattice constants that differed by about 100 standard deviations. Chemical analyses are insufficiently accurate to detect differences in composition at the required sensitivity levels.

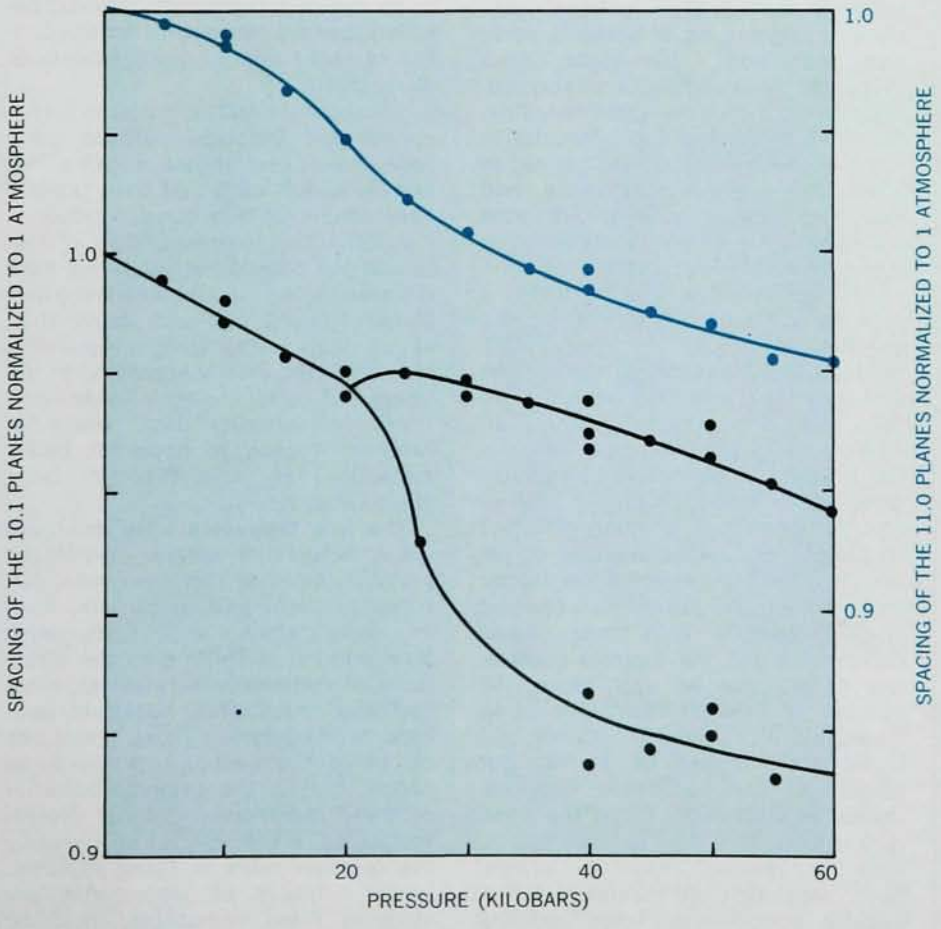
Significant differences have recently been demonstrated in mosaic structure among several spheres of synthetic calcium fluoride ground from the same large single crystal. With wide spreads in mosaicity, other properties may also vary from sample to sample, for example, reaction to radiation. Very few investigations have yet been made of the quantitative effects of radiation damage on integrated intensities.

If the average domain radius, assuming the usual mosaic model for real crystals, is reduced by radiation exposure the extinction will also be reduced as the crystal tends to the ideally imperfect limit. The integrated intensities will therefore increase: Factors of two or more are entirely possible. If radiation damage lowers either the long- or short-range order in the crystal, the intensities will be decreased. Chemical damage may result in intensity changes of either sign. Combinations of these various effects may occur simultaneously. Both the rates and extent of change resulting from these mechanisms is likely to be different; at present we cannot predict the net effect. Figure 6 illustrates some possible variations in the integrated intensity of a given reflection.

Crystal growth

Successful growth of single crystals with interesting properties can lead to great activity in solid-state physics. Recent examples are found in nonlinear optics, lasers and magnetism. The growth of crystals with highly nonlinear optical properties such as lithium niobate and lithium tantalate and the series of tungsten bronze-type structures has led to intensive study of such phenomena as harmonic generation, optical modulation, parametric oscillators and stimulated scattering (PHYSICS TODAY, January 1969, page 38). In turn, the need for more nonlinear optic materials with lower susceptibility to optical damage, higher refractive indexes and birefringence, and wider spectral transmission has stimulated a large effort to grow new crystals with these desirable properties.

The initial choice of materials for possible crystal growth largely depends on a combination of crystallographic and chemical considerations. Although the ultimate goal of "molecular engineering" has by no means yet been realized, the success rate of recent choices indicates substantial



PHASE TRANSITION indicated by splitting of the 10.1 line (corresponding to changes in the 10.1 spacing) in the x-ray pattern of terbium metal powder at high pressure; the 11.0 line (color) does not split. (From reference 2.) —FIG. 5

progress is being made. Experimenters are trying to improve crystal quality by eliminating deviations from stoichiometry and variations in composition, controlling the strain distribution, studying the effects of long- and short-range order parameters on the crystal properties, and detecting and eliminating the presence of electric, magnetic and mechanical twin domains.

The microscopic theory of crystal growth is in a period of rapid development, although it still provides only partial guidance for solving specific growth problems. But a macroscopic approach to the fluid dynamics of convective processes is influencing both the theory and control of crystal growth. For example, experiments like those by John Carruthers and Kurt Nassau[3] (Bell Labs) have pro-

THE MOLECULES OF MOLECULAR BIOLOGY

DAVID HARKER

Although living things are composed of an endless variety of cells, all of them contain similar components. Molecular biology deals with the molecular nature of these components and other substances that strongly affect cell behavior.

The chemical changes that molecules undergo in various environments are almost entirely determined by the ways their atoms are connected together (chemical structures) and the ways their connected atomic complexes are arranged in space (molecular conformation). To understand the molecular changes that constitute the chemistry of life requires knowledge of these three-dimensional atomic arrangements, and biologically oriented structural crystallographers are supplying this knowledge. A great deal of research into the crystal structures of biologically important substances is going on at present, using x-ray diffraction. One might object that most living matter is noncrystalline—indeed, that the less crystalline, the more alive—but the molecules in the crystals are about the same as when they are not in crystals, and x-ray crystallography gives the most complete and accurate information about their atomic arrangements.

The special directions in which x rays are scattered by a crystal depend on the periodicity of the crystal, whereas the intensities of the various individual scattered rays depend on the three-dimensional atomic arrangement in the unit cell, which is the building block of the crystal. Ordinarily one measures the intensities of about ten times as many different scattered rays as the number of parameters needed to define the atomic arrangement and the thermal blurring in the molecule. With three atomic coördinates and six thermal parameters to evaluate for each atom, the number of different intensities to be measured is normally about 100 times the number of atoms, but sometimes one has fewer measurements. In such cases either the accuracy suffers, or it may be even impossible to resolve individual atoms. Such resolution difficulties are frequently encountered when working with crystals of large molecules, such as proteins.

At the moment the most exciting x-ray diffraction studies of biological molecules are those that are giving some information about the structures of molecules of transfer ribonucleic acid (t-RNA). These molecules consist of 77 to 80 nucleotides (organic compounds consisting of a base containing nitrogen linked to a sugar, ribose, which is linked in turn to a phosphate group) bonded into a polymer of molecular weight 25 000. These molecules double back on themselves and apparently have something like the double-helix structure proposed by James Watson and Francis Crick. Each amino acid found in proteins has a t-RNA specifically structured to carry the acid to its proper position in a protein, and then to release it after it is attached to the end of the growing polypeptide chain, which makes up that protein. For this reason the structures of t-RNA molecules are of tremendous interest, because they are responsible for the control of many atomic arrangements in living matter.

Groups at MIT, Princeton, Wisconsin and Chicago—perhaps more now—have crystallized t-RNA's for certain amino acids and have preliminary results on the corresponding x-ray diffraction patterns. The resolution of the data is not yet better than 0.9 nanometer. If the smallest interplanar spacing is much larger than about 0.15 nanometer neighboring atoms are not clearly separated in the image of the molecule calculated from the intensity data. There is, however, reason to hope for better resolution as crystallization techniques improve.

The last few years have produced the structures of several crystallized proteins, most of them enzymes, but a few of them oxygen carriers, such as hemoglobins and myoglobins. Now interest is shifting to the structures of complexes between enzymes and their substrates, substrate analogs, or inhibitors. These structures can reveal the mechanisms of enzyme action, that is the catalytic behavior of these remarkable globular protein molecules, which control so precisely the reaction rates in living systems. Large numbers of laboratories are studying these complexes, including groups at Harvard, Yale, Roswell Park Memorial Institute (Buffalo), a group at Groningen (the Netherlands) and Oxford.

Attempts to crystallize the proteins involved in immunological reactions are beginning to succeed; thus their structures will soon be accessible to x-ray crystallographic methods. Already a few preliminary studies are under way, for example at Johns Hopkins School of Medicine and at the National Institutes of Health.

One very interesting modern development in molecular biology is an attempt to predict the three-dimensional conformation of structures whose chemical connectivity is already known; this subject is called "conformational analysis." The conformations are classified according to their energies and entropies; the ones that correspond to the smallest free energies should correspond to the naturally occurring conformations. Some very successful work along these lines is going on at the University of Madras (India), Kings College of the University of London and Cornell. If the correct assumptions about interatomic potentials within a chemical molecule can be made, we can expect to predict successfully the conformations of the very complicated molecules that are not yet accessible to direct structural studies. Then conformational analysis would become as important to biology as quantum mechanics has been to physics.

X-ray diffraction effects can be observed from noncrystalline materials, such as natural and artificial fibers and so on. These diffraction patterns can allow certain conformations to be ruled out of consideration, but they usually cannot distinguish among a number of related structures, which give closely similar scattering patterns. Attempts are being made to find the structures of bacterial flagellae, the structures of muscle fibers and many other partially ordered biological objects. Indeed one of the very important results of this kind of study is the double helix of Watson and Crick, which is allowed by the experimental work of Maurice Wilkins. There is at present a controversy between two groups, each of which has a favorite structure for collagen. Both structures are compatible with x-ray diffraction evidence, and both give about the same free-energy minimum by conformational analysis.

vided insight into Czochralski crystal pulling. In this technique one grows a crystal by slowly withdrawing a rotating seed crystal that is in contact with the melt. Circulation currents in the melt are simulated (figure 2) by injecting a dye of matching density into a water–glycerine mix. When the crucible and crystal rotate in opposite directions, three circulation regions form; transfer is forbidden by theory.

A crystal-growth technique of considerable potential uses furnaces capable of maintaining up to 100-kilobar pressures and 1300°C temperatures. For example, Massimo Marezio and his coworkers at Bell Labs recently produced single crystals of a new phase of calcium borate, growing them at about 35-kbars pressure and 900°C; the coördination number of calcium had been increased from the normal 8 to 12, that of boron from 3 to 4, and that of oxygen from 3 or 4 to 5.

Proteins and other large molecules

Crystallographers have been trying to solve crystal structures of ever increasing molecular complexity. Two factors are leading to successful crystallographic studies of many proteins and other large molecules: We can now collect x-ray diffraction data from single crystals rapidly and moderately reliably, and we can tackle the phase problem with powerful means developed over the past several years. At the congress, electron-density maps will be reported for 20 proteins, with resolutions as good as 0.25 nanometer in some cases. These data are causing an outpouring of biological and chemical structural information.

The Nobel chemistry prize was indeed well earned by Dorothy Crowfoot Hodgkin (Oxford) for the solution in 1957 of the crystal structure of vitamin B_{12}, whose molecular weight is 1343. Many of the proteins discussed at the congress have molecular weights hundreds of times greater. David Harker, the first to solve a protein structure in the US gives an account of current protein work on page 36.

The recent discovery that long-chain polymers crystallize as lamellae about 15 nanometers thick (see figure 7), in which the polymer chain is folded many times, has led to reëvaluation of the properties of many plastic materials. Chain-folded crystallization appears to be common among many biopolymers, including polypeptides with the alpha-helical conformation and native (double-stranded) DNA. The packing of polynucleotides, as in bacterial viruses, is now being speculated about in terms of chain folding.

To deduce the complete crystal structure one must assign phase angles to the diffracted beam intensities. Until 20 years ago this could generally be done only by trial and error, or by using the location of the heavy atoms to compute phases. Then probability concepts were introduced into the determinations. Now the symbolic addition method of Jerome and Isabella Karle (Naval Research Laboratory) has made phase determination more powerful and simple. These calculational techniques, along with experimental improvements in isomorphous replacement and anomalous-dispersion techniques, have allowed solution of the structure of many large molecules, both natural and synthetic. Crystallographic methods will often take appreciably less time than modern organic chemistry; at the same time they provide detailed steric and geometric information about the molecule.

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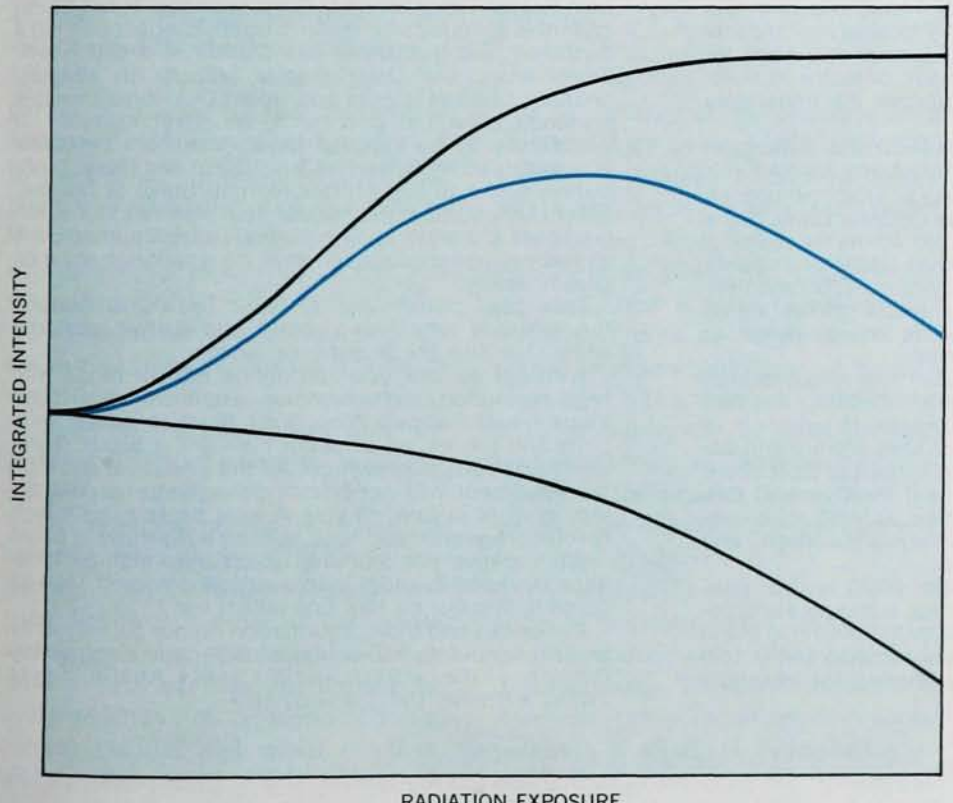
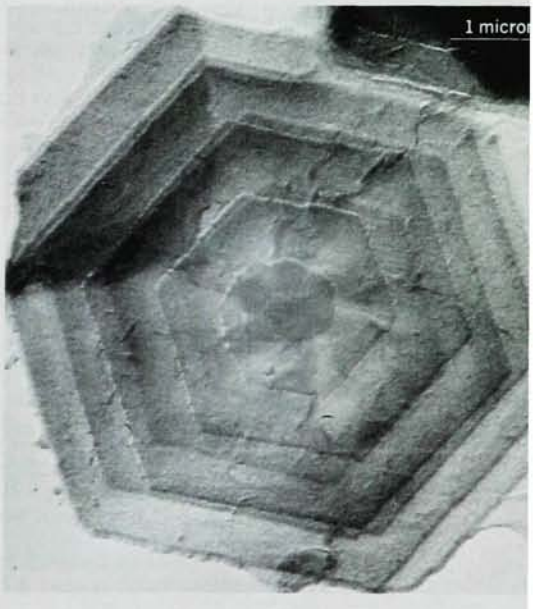


POSSIBLE VARIATION IN THE INTEGRATED INTENSITY of a reflection as a function of radiation damage. The upper black curve illustrates a decrease in extinction, the lower black a reduction in long- or short-range order, and the colored curve a combination. —FIG. 6



MULTILAYER DEVELOPMENT due to growth on a dislocation spiral. Each lamella is about 15 nanometers thick. Polypeptides with the alpha-helical conformation and average length of about 110 nm are oriented with helix axes normal to the lamellar planes. Each molecule spans the lamellar thickness six to seven times by folding back on itself at the broad lamellar surfaces. (From F. J. Padden, H. D. Keith and G. Giannoni, Biopolymers, in press.) —FIG. 7