

CRYSTALLOGRAPHY.

1. INTRODUCTION.

AGAIN this report is far from an annual report in scope—it now has to cover papers published over a period of four years. In its arrangement, we have followed somewhat the plan we adopted last year. The first section deals with one aspect of crystallographic technique, that of neutron crystallography, while the second section describes the crystal structures of organic compounds studied in the four years, 1947—50.

We have again found it impossible to deal with many interesting researches which have by common consent fallen in past years within the scope of crystallographic reports—particularly *X*-ray scattering in liquids and partially ordered systems, such as many high polymers. There are also interesting developments of technique, such as the use of polarised infra-red and ultra-violet radiation in crystal analysis, to which a whole section of the report might well be devoted another year. In connection with crystal optics, the appearance of the new edition of “*Crystals and the Polarising Microscope*,” by Hartshorne and Stuart, is particularly welcome.

2. NEUTRON CRYSTALLOGRAPHY.

Introduction.—A new development has arisen in crystallography with the advent of nuclear piles, namely the application of neutron diffraction to problems of crystal structure. This was briefly mentioned in last year's report on crystallography but otherwise the topic has not been referred to in these pages. It is therefore proposed to survey the subject as a whole.

The idea of neutron diffraction is, of course, not new. As long ago as 1936, Elsasser¹ pointed out the theoretical possibility of the diffraction of slow neutrons by crystalline materials, and in the same year the existence of the phenomenon was shown experimentally by Halban and Preiswerk,² and by Mitchell and Powers.³ Monochromatic neutrons were, of course, not available and the experimental results were not such as to permit of any useful practical application, but nevertheless about a dozen papers on the subject appeared up to 1940, mostly in *Physical Review*.

With the building of nuclear piles the possibility arose of obtaining monochromatic neutron beams of sufficient intensity to put neutron diffraction on an entirely new basis, and since 1946 a steady stream of papers has appeared. Reference will be made at this stage only to some of the more general papers on the subject.^{4–8}

¹ Elsasser, *Compt. rend.*, 1936, **202**, 1029.

² Halban and Preiswerk, *ibid.*, 1936, **203**, 73.

³ Mitchell and Powers, *Phys. Review*, 1936, **50**, 486.

⁴ Wollan and Shull, *Nucleonics*, 1948, **3**, 8, 17.

⁵ Shull and Wollan, *Science*, 1948, **108**, 69.

⁶ Wollan and Shull, *Phys. Review*, 1948, **73**, 830.

⁷ Bacon and Thewlis, *Proc. Roy. Soc.*, 1949, **A, 196**, 50.

⁸ Lonsdale, *Nature*, 1949, **164**, 205.

The first neutron spectrometer to be built was erected at the Argonne National Laboratory in 1945, and was used principally for nuclear-physical experiments requiring a monochromatic beam of neutrons. Serious attention was nevertheless also given at the outset to neutron scattering by crystals, and Zinn,⁹ Fermi and Marshall,¹⁰ and Goldberger and Seitz¹¹ published important papers on this question. The main body of work on neutron crystallography has, however, come from Oak Ridge where Shull and Wollan and their co-workers have published a series of papers which will be referred to in more detail later in the report. Work of this type is also being carried out at Chalk River in Canada, and at Harwell in this country.

With this brief introduction a more detailed account of neutron diffraction will now be attempted and a comparison with *X*-ray diffraction given. Some idea of the experimental techniques involved will be presented and applications to crystallography described. A final section will be devoted to future developments.

The Wave-length of Neutrons.—In a conventional nuclear pile the fast neutrons produced by fission are slowed down by repeated collisions within a "moderator" of heavy water or graphite until they are slow enough to provide further fission. The favourable energy for the occurrence of such fission is obtained when the neutrons are in thermal equilibrium with their surroundings at or about room temperature. These thermal neutrons give rise to further thermal neutrons by the successive processes of fission and slowing-down, and if a collimator is inserted in the pile some of these neutrons will emerge from it in the form of a beam which may be used in neutron-diffraction experiments.

The equivalent wave-length λ of a beam of neutrons of energy E is given by the expression

$$\lambda = \sqrt{(0.081/E)} \times 10^{-8} \text{ cm.}$$

where E is expressed in electron-volts; and the equilibrium temperature in a pile, which is normally in the range 0° to 100° , corresponds to a peak energy of several hundredths of an electron-volt; so that the wave-lengths concerned are of the order of 1 Å., i.e. they are very like the *X*-ray wave-lengths used for crystal analysis and are, of course, similar to the inter-atomic distances in crystals. For example, the peak wave-lengths corresponding to 0° and 100° are 1.9 and 1.63 Å., respectively.⁷

It is therefore to be expected that thermal neutrons will be diffracted by crystals; but, since the distribution of energy among the neutrons in the beam follows approximately the Maxwellian curve appropriate to the equilibrium temperature, there is nothing to correspond to characteristic radiation, and the beam is, in effect, "white." Fig. 1, due to Bacon,¹² gives, for example, the variation of neutron counting rate with wave-length for a typical equilibrium temperature of 50° . It refers to the thermal column of the Harwell pile, in which a mass of graphite ensures that the energies of the neutrons present are, for the most part, in the thermal region.

⁹ Zinn, *Phys. Review*, 1947, **71**, 752.

¹¹ Goldberger and Seitz, *ibid.*, p. 294.

¹⁰ Fermi and Marshall, *ibid.*, p. 666.

¹² Bacon, unpublished data.

In view of this energy spread it is customary to monochromatise the neutron beam for use in neutron crystallography, usually by reflection at a flat crystal surface, although a bent-crystal monochromator has been used for neutron cross-section measurements.¹³ Fig. 1 shows the band of wave-

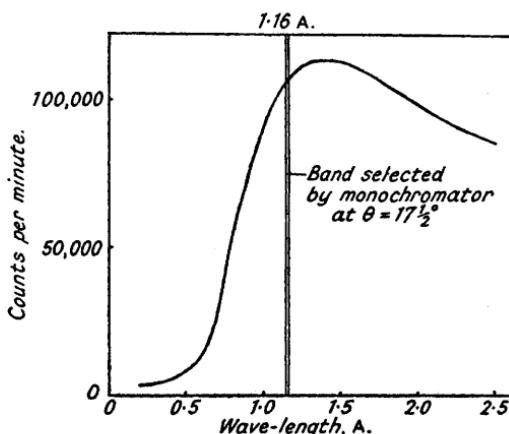


FIG. 1.

Spectrum of thermal neutrons as diffracted by calcium fluoride.

lengths selected by a fluorite monochromator in use at Harwell. It is deliberately chosen to be on the short wave-length side of the peak to avoid the complications that would arise from the presence of an appreciable second-order component in the monochromatised beam.

X-Ray and Neutron Diffraction.—It has been seen that a neutron beam, as it emerges from a pile, is analogous to a beam of "white" X-rays and that it is usually monochromatised for use in neutron crystallography. Only about one thousandth of the neutrons in a collimated pile beam are reflected from the monochromator. Photographic detection of neutrons presents considerable difficulties for neutron crystallography is not generally applicable. In order to achieve a sufficiently high counting rate in the boron trifluoride detectors usually employed, neutron beams of 10^6 – 10^7 neutrons per second are commonly used. To obtain neutrons in these numbers from the nuclear piles at present available, very wide beams must be utilised, the cross sections of which are measured in square inches, whereas those of X-ray beams are, of course, measured in square millimetres. As a result, neutron spectrometers have had to be constructed on a massive scale.^{6, 9, 14, 15} They resemble gargantuan X-ray spectrometers, may weigh several tons and are correspondingly expensive. Recent developments at Harwell suggest that this massive equipment may not always be necessary, but more will be said later about techniques in general. At this stage it is sufficient to point out that neutron diffraction demands different techniques from X-ray diffraction.

¹³ Sawyer, Wollan, Bernstein, and Peterson, *Phys. Review*, 1947, **72**, 109.

¹⁴ Hurst, Pressesky, and Tunnicliffe, *Rev. Sci. Instr.*, 1950, **21**, 705.

¹⁵ Bacon, Smith, and Whitehead, *J. Sci. Instr.*, 1950, **27**, 330.

Not only, however, does neutron diffraction differ from *X*-ray diffraction in the techniques employed, it differs fundamentally in certain underlying phenomena. Perhaps the most obvious difference is in the extremely low absorption of most elements for thermal neutrons. Table I gives the mass absorption coefficients of a number of common elements for thermal neutrons and for *X*-rays ($Fe\ K_{\alpha}$), together with those for lithium, boron, cadmium, and gadolinium which are among the most highly absorbent elements for thermal neutrons. It will be seen that even these elements have mass absorption coefficients which are of only the same order as that of most elements for a comparable *X*-ray wave-length. For other elements, the neutron absorption is very much less indeed.

TABLE I.
X-Ray and Neutron Absorption Coefficients.

Element.	At. No.	Mass absorption coefficient.	
		X-Rays ($\lambda = 1.93\text{ \AA}$.)	Neutrons ($\lambda = 1.8\text{ \AA}$.)
Lithium	3	1.5	5.8
Boron	5	5.8	38.4
Carbon	6	10.7	0.00023
Aluminium	13	92.8	0.005
Iron	26	72.8	0.026
Copper	29	98.8	0.032
Bromine	35	169	0.057
Silver	47	402	0.32
Cadmium	48	417	13.0
Gadolinium	64	199	183.0
Gold	79	390	0.29
Lead	82	429	0.0006

Another difference in absorption is that, whereas for *X*-rays the mass absorption coefficient varies in a regular fashion with atomic number, for neutrons there is no such regularity. The latter fact has no particular bearing on problems of neutron crystallography, but the extremely low value of neutron absorption that occurs in general means that multiple scattering is possible, with a consequent increase in background intensity; and that, for imperfect crystals, extinction plays a much more important part than absorption, with striking effects on the integrated intensity. The latter was first pointed out by Bacon and Thewlis,⁷ and the theory was developed in detail by Bacon and Lowde.¹⁶ It will be recalled that, for *X*-rays and perfect crystals, the integrated reflection is proportional to the structure factor F , "true" absorption playing no part: this is also true for neutrons. In practice, however, crystals are usually "imperfect," and the integrated *X*-ray reflection is then proportional, apart from small extinction effects, to F^2 . In the case of neutron diffraction, on the other hand, the integrated reflection may be controlled almost entirely by secondary extinction. Indeed, for a thick mosaic crystal it is, in general, independent of structure factor, increasing with the degree of mosaic spread. The theory predicts however that, for very thin crystals, the integrated reflection will be proportional to F^2 , and also suggests that there will be a range of

¹⁶ *Acta Cryst.*, 1948, 1, 303.

somewhat greater thicknesses where it will be proportional to F . As pointed out by Bacon and Lowde,¹⁶ the latter result explains the observations made by Fermi and Marshall,⁹ who found in a number of cases that their measured intensities were proportional to F rather than F^2 . Recent quantitative results obtained by Bacon¹² confirm the theory, and it seems fair to conclude that, if single crystals are to be used successfully in neutron crystallography, they will have to be much thinner than those used by Fermi and Marshall. So far, use has been made of transmission through blocks of powdered crystal, where the situation is not complicated by extinction, and where diffracted beams of adequate power may be obtained by using large specimens and neutron beams of large cross-section. The reflecting power of such a block is proportional to F^2 just as for X -rays.

There are other differences between X -ray and neutron diffraction that must be taken into account to complete the picture. For example, neutron scattering is in general spherically isotropic, since such scattering is a nuclear phenomenon. In other words the f -curve takes the form of a horizontal straight line. Lonsdale has suggested⁸ that this means that only "trial and error" methods of structure analysis are possible. In the Reporter's opinion, however, it should be possible in principle to use the usual Fourier methods in neutron crystallography, for example by using the device of an artificial temperature factor. Even so it would appear to be foolish to examine an unknown crystal by neutron diffraction until all possible information had been obtained by X -ray diffraction.

Another difference is concerned with the intensity of scattering per atom. For X -rays, of course, this increases with atomic number and is proportional, other things being equal, to the square of the atomic-form factor; but for neutrons, where the scattering is by the nucleus, it appears to be quite unpredictable. Not only does the scattering power per atom vary at random from atom to atom, but also from isotope to isotope of the same atom; moreover the sign of the scattering amplitude may also vary in the same way. For X -rays the scattered wave from an atom is 180° out of phase with the incident wave; and whereas for neutrons this is also true in most cases, the scattered and incident waves are in phase for certain isotopes, and hence for certain elements. By convention the scattering amplitude is regarded as negative in the latter cases, and it is so shown in Table II, in which X -ray- and neutron-scattering amplitudes are given for a number of elements and individual isotopes. It will be noticed that different isotopes of the same element (*e.g.* lithium and nickel) can have scattering amplitudes of different signs.

In neutron diffraction there is the possibility of much more "background" scatter than in X -ray diffraction. In the latter case some background scatter always results from the temperature effect and from the Compton effect; the excitation of fluorescent radiation and the presence of a disordered or deformed structure in the material under investigation will also contribute appreciably in appropriate cases. Of these possible causes, only three can operate in neutron diffraction, namely the temperature effect and the disorder

and deformation effects, but the absence of the others may be more than compensated for by new effects which have no parallel in X-ray diffraction. One of these, multiple scattering, has already been noted; but the main effect arises from the fact that almost all structures are disordered from the point of view of neutron scattering. A disordered structure is essentially a structure in which the atomic scattering power varies randomly from site to site in the structure. In X-ray diffraction, this arises in a disordered alloy, for example,

TABLE II.
*Ordered scattering amplitudes * for X-rays and thermal neutrons.*

Element.	At. No.	Scattering amplitude. ¹⁷		Element.	At. No.	Scattering amplitude. ¹⁷	
		X-Rays (for $\sin \theta/\lambda = 0.5$) $\times 10^{-12}$ cm.	Thermal neutrons $\times 10^{-12}$ cm.			X-Rays (for $\sin \theta/\lambda = 0.5$) $\times 10^{-12}$ cm.	Thermal neutrons $\times 10^{-12}$ cm.
H	1	0.02	-0.40	Co	27	3.42	0.28
D	1	0.02	0.64				1.03
Li	3	0.28	{ ⁶ Li ⁷ Li -0.25	-0.18	Ni	28	3.58
Be	4	0.39	0.78	Cu	29	3.75	0.76
C	6	0.48	0.64	Zn	30	3.92	0.59
N	7	0.54	0.85	Ge	32	4.23	0.84
O	8	0.62	0.58	As	33	4.40	0.63
F	9	0.75	0.55	Se	34	4.54	0.89
Na	11	1.14	0.35	Br	35	4.71	0.67
Mg	12	1.35	0.44	Rb	37	5.05	0.55
Al	13	1.55	0.35	Sr	38	5.19	0.57
S	16	1.93	0.31	Zr	40	5.56	0.62
Cl	17	2.04	0.99	Nb	41	5.70	0.69
K	19	2.23	0.35	Mo	42	5.87	0.64
			0.49	Pd	46	6.52	0.63
Ca	20	2.37	{ ⁴⁰ Ca ⁴⁴ Ca 0.18	0.49			0.61
Ti	22	2.68	-0.38	Ag	47	6.71	{ ¹⁰⁷ Ag ¹⁰⁹ Ag 0.83
V	23	2.85	<0.09 †	Sn	50	7.22	0.61
Cr	24	2.99	0.37	Sb	51	7.42	0.54
Mn	25	3.13	-0.33	I	53	7.75	0.52
			0.96	Cs	55	8.09	0.49
Fe	26	3.27	{ ⁵⁴ Fe ⁵⁶ Fe ⁵⁷ Fe 0.42 1.00 0.23	Ta	73	11.25	0.70
				W	74	11.42	0.51
				Pt	78	12.17	0.95
				Au	79	12.37	0.77
				Tl	81	12.70	0.75
				Pb	82	12.90	0.96
				Bi	83	13.10	0.89

* For meaning of ordered amplitude see preceding paragraph.

† Sign of amplitude in doubt owing to small magnitude.

from the random occurrence at the various atomic sites of different kinds of atom. In neutron diffraction it can actually arise for a single element, since the nuclear scattering power may vary in a random fashion from site to site on account of the random distribution of isotopes and sometimes of nuclear spins. It has already been seen that different isotopes of the same element have, in general, different scattering powers, and the existence of isotope-disorder should be at once apparent. The existence of spin-disorder also

¹⁷ Figures except those for Tl, kindly supplied by Dr. C. G. Shull. [Added in proof: These figures have now been published—Shull and Wollan, *Phys. Review*, 1951, **81**, 527.]

¹⁸ Winsberg, Meneghetti, and Sidhu, *ibid.*, 1949, **75**, 975.

follows when it is realised that the scattering amplitude of a nucleus will be different according as its spin is parallel or antiparallel to that of the neutron, and that spins, like isotopes, are randomly distributed. Where the nucleus has no spin, as in the case of isotopes of even atomic mass above ^{14}N , there will, of course, be no spin-disorder. In some cases, *e.g.* hydrogen, the disordered scattering is so great that the "Bragg" or ordered scattering amplitude (*i.e.* the amplitude scattered into the Bragg peaks) is very much less than the total scattering amplitude, but in many others¹⁰ there is evidence that the dependence of scattering amplitude on spin orientation and isotopic constitution is not so marked. With hydrogen the total scattering amplitude is 2.5×10^{-12} cm. whereas the ordered scattering amplitude is only 0.4×10^{-12} cm., a difference that arises largely from spin-disorder. In deuterium on the other hand, although the ordered amplitude is not much greater, namely 0.63×10^{-12} cm., the spin-disorder is relatively low, and it is often advisable, therefore, to carry out neutron-structure determinations on deuterated compounds if possible. This has been done for sodium hydride¹⁹ and ice²⁰ with results to be described below.

There are four other ways in which neutron diffraction differs from X-ray diffraction. The first is concerned with the binding of the nuclei, and the second with inelastic scattering of the neutrons. In addition, further scattering (both elastic and inelastic) occurs for ferromagnetic * and strongly paramagnetic substances on account of an interaction between the magnetic moment of the neutrons and the orbital magnetic moments of the atomic electrons. Finally there is the fact that neutrons are not, in general, polarised on scattering, except in a few cases where polarisation arises from the effect of magnetic fields.

We will now revert to binding and inelastic scattering effects. The neutron-scattering amplitude for an element is different according as the atoms are free (as in a gas) or bound (as in a liquid or solid). The ratio of these two amplitudes is $A/(A + 1)$ where A is the mass number of the isotope concerned, and it will be seen that this ratio is effectively unity for all but light atoms.

The possibility of appreciable inelastic scattering arises from the fact that the frequency of vibration of the thermal neutrons is of the same order as that of the atomic vibrations (about 10^{13} per second). In consequence a neutron will lose an appreciable fraction of its energy in exciting a quantum of vibrational energy; in other words appreciable inelastic scattering (*i.e.* scattering with a change of wave-length) will occur, which will again manifest itself as an increase in background scattering. Weinstock²¹ has calculated, for a "free" atom of polycrystalline iron, that 0.6% of the scattering will be inelastic at absolute zero and that this will rise to 19% at 1000°K. Cassels²²

¹⁹ Shull, Wollan, Morton, and Davidson, *Phys. Review*, 1948, **73**, 842.

²⁰ Wollan, Davidson, and Shull, *ibid.*, 1949, **75**, 1348.

²¹ Weinstock, *ibid.*, 1944, **65**, 1.

²² Cassels, "Progress in Nuclear Physics," (Frisch), Butterworth-Springer, London, 1950, Ch. 8.

* Antiferromagnetic substances are referred to later.

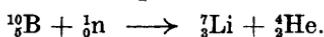
has more recently treated the problem in some detail. In the corresponding X-ray case the loss of energy is too small to be noticed, since the frequency of vibration of X-rays is about 10^{18} per sec. and the quantum energy is therefore of an entirely different order of magnitude.

To summarise, then, the main differences between X-ray and neutron diffraction may be stated as follows :

Phenomenon.	X-Rays.	Neutrons.
Absorption	Regular variation with increasing atomic number.	Irregular variation. Absorption nearly always small. Background increased by multiple scattering.
Extinction	Subordinate to absorption.	Generally outweighs absorption so that large single crystals impracticable for much structure work. Powders must be used in these cases.
Bragg scattering	Electronic atomic-form factor exists. Scattering power per atom increases regularly with atomic number. Scattered wave 180° out of phase with incident wave.	Nuclear scattering spherically isotropic. Scattering power varies at random. Scattered wave usually 180° out of phase, but sometimes in phase.
Effect of thermal vibrations	Intensity reduction according to Debye-Waller formula. Diffuse scattering. No measurable change in wavelength.	Similar phenomena to be expected, but also appreciable amount of inelastic scattering with large change in wave-length and increased background intensity.
Polarisation	Scattered wave is polarised.	Scattered wave is not polarised except for magnetic effects
Isotope effect	All isotopes of same element have same scattering power.	Isotopes may have different scattering powers, resulting in isotope-disorder and increase in background intensity.
Spin effect		Scattering power is different, for finite spin, according as this is parallel or anti-parallel. Results in spin-disorder, with increase in background scattering.

Experimental Techniques.—As already indicated, measurements in neutron crystallography are usually made with the aid of wide neutron beams and large spectrometers in which provision is made for monochromating the beam, and the neutrons are detected by means of a boron trifluoride counter. Laue photographs have been taken by Wollan, Shull, and Marney²³ by a method involving the use of an "intensifying screen" of indium foil, which emits β -rays when bombarded by neutrons; but, apart from this one type of application, photographic methods have not been used in neutron-diffraction work up to the present. The reason for this is obvious when one considers that the exposure time for even a Laue photograph is about 10 hours.

The boron trifluoride counter depends on the reaction



²³ Wollan, Shull, and Marney, *Phys. Review*, 1948, **73**, 527.

It is arranged to record the α -particles emitted in this reaction, but is insensitive to γ -rays. Ordinary boron contains only about one part in five of the ^{10}B isotope, so that whenever possible separated ^{10}B is used to make the boron trifluoride gas with which the counter is filled; the efficiency of the counter may then be as high as 80 or 90%.

Great care is necessary to shield the counter from unwanted radiation, and it is also necessary to keep a watch on variations in the intensity of the incident neutron beam by some form of a monitor, for example a fission chamber may be inserted in some convenient place in the pile. The monochromating crystal may take the form of the usual flat plate or the crystal may be cut obliquely, as first recommended by Stephen and Barnes²⁴ and later used by Fankuchen²⁵ for X-ray work, so as to "foreshorten" the reflected beam with consequent increase of intensity. The type of equipment in use at Oak Ridge⁸ is a restricted double-crystal instrument, using sodium chloride or a metal single crystal as the monochromating crystal, capable of employing a single wave-length only.* A true double-crystal instrument is in use at Harwell,¹⁵ in which both monochromating crystal and specimen may be rotated at will. This spectrometer is also mobile. As in most of the neutron spectrometers so far used the counter arm is arranged to turn at twice the angular speed of the specimen table, so as to enable the counter to receive the reflected beam for single crystal work and to maintain the symmetrical transmission position for powder work.

A rather different type of technique is also being developed at Harwell²⁶ in which an attempt is being made to reduce the dimensions of the neutron spectrometer to the X-ray scale, and to use small single crystals, again as in X-ray techniques. The use of such crystals should, of course, overcome the extinction problems already referred to, and the lack of neutrons is being overcome by not monochromatising the beam (thus gaining a very large factor), setting up the specimen in the reflecting position for a given plane and wave-length, and placing a miniature counter (made of multiple boron-coated foils)²⁷ in the correct position to receive the reflected beam. In this way, a single measurement of counting rate gives the required integrated reflection. Difficulties will undoubtedly arise from the presence of unwanted high-order components in the beam, and, of course, reflections must not overlap; but preliminary results have been very encouraging, and the ratio of peak counting rate to background appears to be such that hydrogenous crystals may be examined directly without the need for deuteration. The possibility of using orthodox methods is being examined, and the first results suggest that, given an increase in neutron flux of only ten or twenty over that available in the Harwell pile,† monochromatic beams might be used which would permit rotating-crystal techniques exactly analogous to those used in everyday X-ray analysis.

²⁴ Stephen and Barnes, *Nature*, 1935, **136**, 793. ²⁵ Fankuchen, *ibid.*, 1937, **139**, 193.

²⁶ Lowde, *ibid.*, 1951, **167**, 243.

²⁷ *Idem, Rev. Sci. Instr.*, 1950, **21**, 835.

* [Added in proof.] A true double-crystal instrument is now in operation at Oak Ridge.

† Such as the flux provided by the heavy-water pile at Chalk River.

Applications of Neutron Diffraction to Crystallography.—The first possibility that suggests itself, when the phenomenon of neutron diffraction by crystals is considered, is that of the determination of the positions of light atoms in a structure. It is well known that it is very difficult, and often impossible, to determine by *X*-ray analysis the positions of light atoms in a structure in which heavy atoms are also present, since the contributions of the latter swamp those of the former. In the case of neutron diffraction, however, since the scattering powers of all atoms are roughly of the same order, it should clearly be possible to determine the positions of light atoms in the circumstances considered. In particular it should be possible to determine the positions of hydrogen atoms, although, as already explained, the relatively high background scattering from hydrogen makes it advisable to substitute deuterium if possible. The first work of this kind was done by Shull, Wollan, Morton and Davidson¹⁹ on sodium hydride and sodium deuteride. They showed that the structure is the sodium chloride structure and found, as expected, a much greater amount of background scatter with sodium hydride than with the deuteride. Also, owing to the fact that sodium and deuterium scatter neutrons with a positive scattering amplitude and hydrogen scatters with a negative scattering amplitude, a marked reversal of the relative intensities of the 111 and 200 reflections was observed in sodium hydride and sodium deuteride.

Further work on the structural positions of hydrogen atoms, this time by Wollan, Davidson, and Shull,²⁰ has been carried out on ice. Ice made from heavy water (D_2O) was used and maintained at -90° during the experiments; from the results it was possible to decide between the various structures that had been proposed, although the resolution was not sufficient to enable all the lines to be separated. Intensity measurements were made on an absolute scale, and supported the model proposed by Pauling on the grounds of the existence of residual entropy at low temperatures, in which the hydrogen molecules possess some randomness, one hydrogen atom and one only lying on each of the lines joining neighbouring oxygen atoms. Since the oxygen atoms are arranged tetrahedrally this means, in effect, that there are, on the average, four half-atoms of hydrogen arranged tetrahedrally around each oxygen atom, as shown in Fig. 2.

Such a random type of structure should give rise to disordered scattering of its own, and such disordered scattering was indeed observed, the measured and calculated values agreeing quite well.

A second type of application, which also utilises the difference between the relative scattering powers of different elements for *X*-rays and neutrons, is the demonstration by Shull and Siegel²⁸ of the existence of superlattice lines in ordered samples of FeCo and Ni₃Mn. In these two alloys the *X*-ray-scattering powers of the elements involved are practically identical, whereas the neutron-scattering powers, as can be seen from Table II, are sensibly different, indeed manganese has a negative scattering amplitude. In consequence Shull and Siegel were able to reveal the existence of superlattice

²⁸ Shull and Siegel, *Phys. Review*, 1949, **75**, 1008.

lines which could not be obtained by *X*-ray methods. Conversely, as might be expected, they were unable to show the existence of such lines in Cu₃Au by neutron diffraction, although *X*-rays show them up quite clearly.

Shull and Siegel, in this connection, make an interesting suggestion, based on the fact that the neutron scattering amplitudes of various isotopes may vary not only in magnitude but in sign. They take the case of nickel, for which the scattering amplitude is +0.3 for ⁶⁰Ni and +1.41 for ⁵⁸Ni, and compare it with manganese, for which the elemental scattering amplitude is -0.32; and suggest making up an alloy Mn⁶⁰ Ni, for which the intensities of the usual diffraction lines should be vanishingly small, while the super-lattice lines should be quite strong.

Other applications of a metallographic nature have been carried out by Sidhu,²⁹ who showed, by transmitting monochromatic neutrons through solid solutions and mixtures of titanium carbide and tungsten carbide, that the scattering power was related in a definite way to the degree of solid

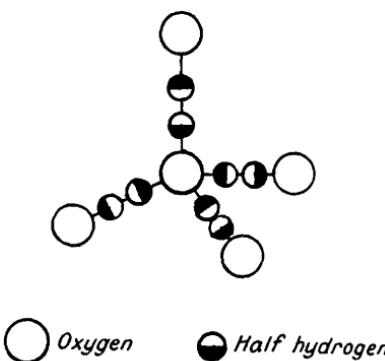


FIG. 2.

solution obtaining; and by Arnold and Weber,³⁰ who showed that the effects of the preferential orientation of aluminium on the observed intensities of neutron reflection agreed, for various orientations, with those expected.

Naturally a considerable amount of work has been devoted to measurements of scattering amplitude, since these are essential before neutron crystallography can be developed. As will be seen from Table II values for many elements and some separated isotopes are now known.

Work has been carried out on liquids by Chamberlain,³¹ and on gases by Alcock and Hurst³² and Spiers.³³ Chamberlain's results on sulphur, lead, and bismuth agree well with those obtained by *X*-ray examination. Alcock and Hurst, and Spiers, working on oxygen, carbon dioxide, and deuterium made the interesting discovery that the correct but complex and laborious quantum-mechanical method of calculating the neutron scattering by a gas gives a result not very different from a semi-classical calculation in which

²⁹ Sidhu, *J. Appl. Phys.*, 1948, **19**, 639.

³⁰ Arnold and Weber, *Phys. Review*, 1948, **73**, 1385. ³¹ Chamberlain, *ibid.*, 1950, **77**, 305.

³² Alcock and Hurst, *ibid.*, 1949, **75**, 1609.

³³ Spiers, *ibid.*, 1949, **75**, 1765.

the neutron is represented by a wave and the molecule by a rigid system of point scatterers, the normal procedure for *X*-ray scattering being used.

An application of a somewhat different kind has recently been reported by Bacon,³⁴ who has studied the electron distribution in graphite by a comparison of *X*-ray and neutron intensities. The *X*-ray intensity of the $10\bar{1}0$ line relative to that of the $11\bar{2}0$ is found to be about 85% too high, and that of the $10\bar{1}1$ relative to the $11\bar{2}2$ to be about 80% too high, and Franklin³⁵ has suggested that this can be explained if the *L*-electrons are not distributed spherically about the carbon nucleus but are concentrated about the centres of the C-C bonds. If the explanation is indeed concerned with electron distribution and not with atomic positions the corresponding intensities obtained by neutron diffraction should show no anomalies since the scattering centres are the nuclei and the electrons play no part. In fact Bacon finds no anomalies, although he restricts his comparison to the ratios of the theoretical and measured intensities of the pairs of lines $10\bar{1}0$ and $10\bar{1}1$, and $11\bar{2}0$ and $11\bar{2}2$, owing to lack of resolution.

Another novel application of neutron diffraction is to the detection of antiferromagnetism.³⁶ An antiferromagnetic material is one in which below a certain temperature, the Curie temperature, the magnetisation directions of neighbouring pairs of atoms are opposed, so that no net spontaneous magnetisation exists. Above the Curie temperature the thermal energy is sufficient to overcome the tendency of the atoms to set themselves in anti-parallel pairs and the behaviour is that of a normal paramagnetic substance. Since, as already mentioned, there is magnetic scattering of neutrons in the case of certain magnetic atoms, the possibility arises of the existence of superlattice lines in the antiferromagnetic state, owing to the different scattering amplitudes of the parallel and antiparallel atoms. In manganese oxide, which has the sodium chloride structure, Shull and Smart have shown very beautifully the presence of magnetic superlattice lines below the Curie point (122°K.) of this material. At these temperatures the chemical (and *X*-ray) unit cell has a side of 4.43 \AA. whereas the magnetic unit cell side is 8.85 \AA. Similar effects have also been found for α -ferric oxide. Neutron diffraction has thus provided a direct way of detecting the orientation of magnetic moments.

Future Developments.—Future developments in such a new subject as neutron crystallography are difficult to forecast, but it seems reasonable to assume that work will continue on the determination of the positions of hydrogen and other light atoms in simple substances; and that this will be extended to more complex structures as suitable methods are developed and single-crystal techniques are perfected, as they must be if adequate progress is to be maintained. This stage of the development will call for the closest co-operation between *X*-ray and neutron diffraction to make full use of the fact that, in effect, we can alter the relative scattering powers of the atoms in a structure, and sometimes the scattering phases, although the atoms them-

³⁴ Bacon, *Nature*, 1950, **166**, 794. ³⁵ Franklin, *ibid.*, 1950, **165**, 71.

³⁶ Shull and Smart, *Phys. Review*, 1949, **76**, 1256.

selves remain in exactly the same configuration. Work on metallic order-disorder will also no doubt proceed where the scattering powers of the metals concerned warrant it, as, for example, in the brasses, and there is undoubtedly scope for the determination of structures containing atoms which are close neighbours in the Periodic Table, and for which the neutron-scattering amplitudes may differ more than the *X*-ray-scattering amplitudes. New types of application, such as to antiferromagnetism and to problems of electronic structure, will presumably continue to arise. One such application, suggested by Cassels,³⁷ is to the study of atomic vibrations by the investigation of the changes of wave-length that occur when inelastic scattering takes place.

Problems concerned with the determination of the nature or degree of preferential orientation may well present a wide scope for neutron crystallography, since the whole body of a specimen may be examined, and not only its surface. Indeed this possibility of examination in depth may well turn out to be of great importance for many types of problem. It should be possible to make measurements on large pieces of material and average the results over a considerable volume, which would be quite impossible by *X*-ray examination owing to the large absorption involved. It should, for example, be possible to determine the orientation of large single crystals which could not otherwise be examined.

Another possible type of application is to phenomena which are difficult to deal with by *X*-rays on account of the falling off in scattering power with increasing angle. For example problems could be attacked which are concerned with the effects of temperature or other disturbing influences on the stability or nature of the atomic arrangement. In much of this work, as already indicated, it will be advantageous if not essential to combine the results of *X*-ray and neutron diffraction; partly because they will in so many respects turn out to be complementary, and partly because the pressure of work on any one neutron spectrometer is likely to be heavy. It seems desirable indeed to restrict the use of neutron diffraction to critical experiments as much as possible, so as to prevent the overloading of the facilities available, and it is clearly undesirable to carry out experiments by neutron diffraction that can be done just as well by *X*-rays. One should obtain all the information possible by *X*-ray examination and turn to neutron diffraction only when necessary. In this way it should be possible to make the best use of this powerful new crystallographic tool.

J. T.

3. ORGANIC COMPOUNDS.

In early Reports on crystallography, the organic compounds on which a detailed *X*-ray analysis was carried out were rather few, and these were often grouped with similar-sized inorganic molecules as a combined group—molecular crystals. Any measurements that led to a set of proposed atomic positions within the crystal of an organic compound appeared a notable achievement. Now we recognise that an approximate structure analysis,

³⁷ Cassels, private communication.

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giving atomic positions based even on calculated electron densities can be carried out relatively easily by present methods for most types of organic compound, crystalline at ordinary temperatures, and with molecular weights of less than about 200. We have about 120 such analyses to report this year; these provide a variety of interesting evidence on the way in

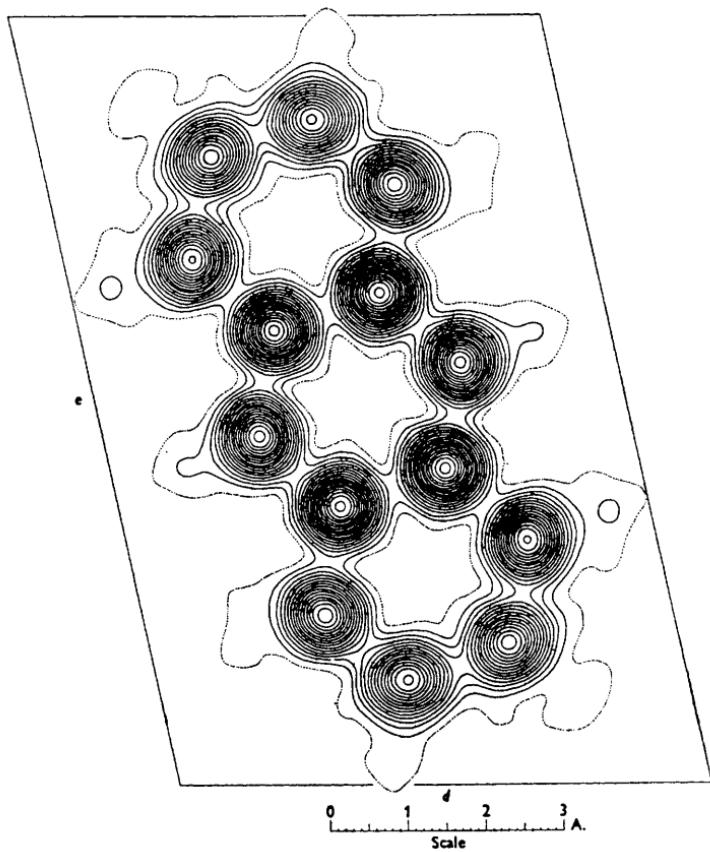


FIG. 3.

A section through the plane of the anthracene molecule. Electron-density contours are at intervals of $\frac{1}{2}$ e. \AA^{-3} , the first one dotted.

[Reproduced, by permission, from *Acta Cryst.*, 1950, **3**, 254.]

which molecules pack in crystals and on the factors determining the disposition in space of non-bonded atoms, while as many as twenty of the total number lead to the direct deduction of the correct chemical or stereochemical formulation of molecules of imperfectly known structure. But it is clear that the conditions under which the exact measurement of bond lengths and electron densities can be achieved through X-ray analysis have to be carefully considered in relation to each individual structure. In only a handful of the structure analyses described can the bond lengths be

considered to be accurate to within ± 0.02 Å., limitations being imposed in most cases either by the nature of the available experimental data or by incomplete refinement of the electron-density series.

In the most careful structure analyses reported, such as those of threonine,³⁸ naphthalene,³⁹ and anthracene,⁴⁰ the electron-density distribution can be calculated sufficiently accurately to provide evidence of the positions of hydrogen atoms (compare Fig. 3), but only very tentative conclusions can yet be drawn, even in cases such as these, on the character or shape of the chemical bonds. Brill⁴¹ has re-examined the structure of diamond from this point of view, and has shown that the differences between observed and calculated structure factors for diamond, summed as a Fourier series, do give an electron distribution which is most marked along the line joining the two atoms—the covalent bond; here it corresponds to a density of about $\frac{1}{2}$ — $\frac{3}{4}$ electron per bond. In graphite, too, as mentioned above, deviations between calculated and observed structure factors can be correlated with an asymmetric electron-density distribution. In both of these structures there have been interesting new measurements of lattice constants. Lonsdale finds that the carbon–carbon distance varies a little in different diamonds from 1.54465 to 1.54440 Å.,⁴² figures which agree well with the mean value given by Riley, 1.54453 Å.⁴³ In graphite the *c* dimension varies with crystallite size—it appears to be an almost linear function of the reciprocal of the number of carbon layers.⁴⁴ In certain carbons, produced by pyrolysis of polydichloroethylene, highly perfect graphitic layers about 16 Å. across have been shown to be present, usually arranged in pairs at a mean distance of about 3.7 Å.⁴⁵ Such graphitic layers are not much larger than the largest aromatic molecules of which detailed X-ray analyses exist.

Some of the general principles determining the ways in which molecules pack in organic crystals have been the subject of a number of recent reviews,⁴⁶ and were also discussed in an earlier Report.⁴⁷ As more crystal structures are analysed, we can examine the situation in greater detail. It is possible to collect groups of compounds that fall into well-defined crystal-structure types and then to examine the deviations that occur in individual cases on account of the actual peculiarities of molecular shape or inter-atomic attractive forces. A number of such structure types have been recognised for a long time. For example, small roughly spherical molecules such as tetrinitromethane⁴⁸ or quinuclidine⁴⁹ pack in crystal

³⁸ Shoemaker, Donohue, Schomaker, and Corey, *J. Amer. Chem. Soc.*, 1950, **72**, 2328.

³⁹ Abrahams, Robertson, and White, *Acta Cryst.*, 1949, **2**, 233, 238.

⁴⁰ Mathieson, Robertson, and Sinclair, *ibid.*, 1950, **3**, 245, 251.

⁴¹ *Ibid.*, p. 137.

⁴² *Phil. Trans.*, 1947, **240**, *A*, 219.

⁴³ *Nature*, 1944, **153**, 587.

⁴⁴ Bacon, *Acta Cryst.*, 1950, **3**, 137. ⁴⁵ Franklin, *ibid.*, p. 107.

⁴⁶ Macgillavry, *Chem. Weekblad*, 1948, **44**, 169; Kitaigorodski, *Uspekhi Fiz. Nauk.* 1948, **34**, 122; *Uspekhi Khim.*, 1948, **17**, 287.

⁴⁷ Powell, *Ann. Reports*, 1946, **43**, 88. Oda and Matsuba, *X-Rays*, 1950, **6**, 27.

⁴⁸ Nowacki, *Helv. Chim. Acta*, 1946, **29**, 1798.

structures based on body-centred or face-centred cubic close packing. It is characteristic that at ordinary temperatures these crystals have too high a symmetry corresponding to molecular disorder or rotation. Recent structure-factor calculations, however, indicate that disorder is not complete—there are usually certain preferred orientations of the molecular axes in the crystals. In hexamethylenetetramine one can see the situation at the other end of the order-disorder scale. Calculations by Schaffer⁵⁰ show that the best agreement with the observed structure factors can be obtained by assuming that the molecule is performing anisotropic oscillations—the calculated root mean square amplitude normal to the radius joining an atom to the molecular centre is 0.26 Å. With short-chain molecules, somewhat similar conditions are found. The chain axes may take up roughly criss-cross positions in relation to one another, and rotation or oscillation is usual at high temperatures. As the chain length increases, parallel chain packing in at least one layer is the rule, though in succeeding layers various crossed arrangements are being discovered in the structures studied. With small aromatic molecules two varieties of packing are common—either parallel disc packing, with an interval between layers of about 3.5 Å., similar to graphite, or a criss-cross arrangement with the disc centres in nearly hexagonal close packing. The first is shown by hexamethylbenzene, several pyrimidines,⁵¹ and coronene with one cell dimension 3.5–4.8 Å., the second by durene, aniline hydrochloride,⁵² dibenzyl, and many others, with the shortest cell dimension between 5.3 and 6.5 Å.

The condition of close packing may be disturbed by the existence of particular active groups in the molecule, each of which favours certain types of arrangement of neighbouring atoms. Regular co-ordination polyhedra about ions can seldom be established in organic crystals, but there is a marked tendency for the co-ordination numbers and interionic distances found among inorganic crystals to be preserved. Thus sodium has six oxygen neighbours in sodium benzylpenicillin,⁵³ potassium six in potassium decanoate (caproate),⁵⁴ seven in potassium benzylpenicillin,⁵³ calcium eight⁵⁵ and strontium eleven⁵⁶ in calcium and strontium formates, the form of the co-ordination polyhedra being in all cases quite irregular. In the case of negative ions, such as the halogens, the co-ordination polyhedra are smaller—usually only three or four atoms are involved⁵²—and the position of these often suggests hydrogen bonding. When halogens occur in the un-ionised state, the molecules are frequently so arranged that the halogen atoms of neighbouring molecules are in contact—presumably owing to the greater contribution they make to van der Waals interaction. A particularly striking example is provided by the three varieties of *p*-iodo-

⁵⁰ *J. Amer. Chem. Soc.*, 1947, **69**, 1557.

⁵¹ Clews and Cochran, *Acta Cryst.*, 1948, **1**, 4. ⁵² Brown, *ibid.*, 1949, **2**, 228.

⁵³ Crowfoot, Bunn, Rogers-Low, and Turner-Jones, "The Chemistry of Penicillin," Princeton Univ. Press, 1949, p. 310.

⁵⁴ Vand, Lomer, and Lang, *Acta Cryst.*, 1949, **2**, 214.

⁵⁵ Nitta and Osaka, *X-Rays*, 1948, **5**, 37. ⁵⁶ Nitta and Sailo, *ibid.*, 1949, **5**, 89.

N-picrylaniline, in all of which the iodine atoms of neighbouring molecules are within the van der Waals distance of one another.⁵⁷ Again, wherever hydroxyl or amino-groups are present hydrogen-bonding systems can be traced. Some of these form particularly stable types which are repeated with variations, e.g., substitution of nitrogen or chlorine for oxygen, in a number of crystal structures. One might expect, for example, a close relation to exist between the system found in phloroglucitol dihydrate⁵⁸ and diammoniate⁵⁹ where the water or ammonia molecules link three neighbouring phloroglucitol molecules together and are themselves linked through a fourth bond. It is more surprising that a similar system is found in 2-hydroxy-4 : 6-dimethylpyrimidine dihydrate⁶⁰ where a planar molecule is substituted for the puckered cyclohexane ring.

Distances described by different authors as hydrogen bonds range from all lengths between 2.51 Å. in oxalic acid dihydrate to 3.2 or 3.3 Å. in compounds involving nitrogen (the term has even been used for the N . . . HC distances in hexamethylenetetramine which are 3.88 Å. long!). It is clear that very varying degrees and probably also types of interaction are involved in different structures. Within the range of "hydrogen-bonded" distances there are also now observed a number of short distances involving carbon to which the term is not usually applied. Some of these, as for example, the short contact CH . . . O, 3.28 Å., in threonine, seem to be forced on the molecule by packing considerations. Others, such as the distance, 2.66 Å. in *p*-nitroaniline,⁶¹ between one oxygen and the benzene ring carbon atom, appear to have a more specific character. A particularly interesting example is provided by the silver perchlorate–benzene complex.⁶² Here each silver ion is at a distance of about 2.6 Å. from two carbon atoms of each of two benzene rings, an arrangement which suggests π-bonding. The perchlorate ion is pushed away from one side of the silver to make room for the benzene rings.

Once normal stereochemical standards of molecular shape have been established, it becomes interesting to examine the conditions under which distortions from these occur. The necessity for a special packing, or the formation of a particularly stable hydrogen-bond system, appears sufficient to deflect the bond direction between an atom and attached benzene ring from the normal position directed to the ring centre. In tetraphenylcyclobutane,⁶³ for example, the deflection of one such bond is 7° from the plane of the ring. The distortion of an aliphatic chain from the planar zig-zag form would be expected to be much easier; so far, one or two examples only have been observed. A distortion from the planar form of the benzene ring itself must, on the other hand, be much more difficult. In the only

⁵⁷ Grison, *Acta Cryst.*, 1949, **2**, 410.

⁵⁸ Anderson and Hassel, *Acta Chem. Scand.*, 1948, **2**, 527.

⁵⁹ *Idem*, *Nature*, 1949, **163**, 721. ⁶⁰ Pitt, *Acta Cryst.*, 1948, **1**, 168.

⁶¹ Abrahams and Robertson, *ibid.*, p. 252.

⁶² Rundle and Goring, *J. Amer. Chem. Soc.*, 1950, **72**, 5337.

⁶³ Dunitz, *Acta Cryst.*, 1949, **2**, 1.

example, di-*p*-xylylene,⁶⁴ the distortion is forced by covalent bonds within the molecule.

Another aspect of the X-ray crystallographic investigation of organic compounds is the use of crystallographic data as a means of identification. This subject has been reviewed recently by Franzen⁶⁵ and by Bannister⁶⁶ who have described both morphological and X-ray methods. The forthcoming publication of the first volume of the Barker index should encourage some return to the first method. The body of data in the powder index on organic compounds is not so far very great, and the problem of deciding which compounds should be included in it is one of considerable interest and importance. In many cases an identification of an organic compound is undertaken with reference to one particular investigation, *e.g.*, to distinguish different penicillins or to identify their degradation products with synthetic specimens^{53, 67} or to show that gramicidin yields on hydrolysis a mixture of *D*-valyl-*L*-valine and *L*-valyl-*D*-valine.⁶⁸ Data on many of these compounds would be doubtfully useful in a general index, while other data collected, *e.g.*, on a series of constituents of explosives,⁶⁹ ought to be incorporated. There are also certain special warnings that have to be attached to the use of crystallographic data in general. More complicated molecules may often crystallise in polymorphic modifications which show very little tendency to be converted one into the other, for example, the three forms of glycylglycine. Often also the crystal structure may be easily deformed or affected by the exact conditions of crystallisation and this, in turn, affects the appearance of the powder photographs. Stosick⁷⁰ has pointed out that a number of the 'polymorphic' modifications of soaps can be explained in terms of crystals with varying degrees of disordered structure and not in terms of phase change.

One interesting point is the occasional possibility of effecting the identification, by crystallographic means, of a natural, optically active isomer with molecules in a synthetic DL-preparation. The vast majority of DL-preparations crystallise as racemic crystals containing both *D*- and *L*-molecules and often having crystal structures very different from those of the separated *D*- and *L*-isomers. Direct identification of the molecular species present by crystallographic means is then, of course, impossible. Not infrequently, however, the crystal structures of the racemic crystals bear a marked resemblance, allowing for the presence of different symmetry operations, to those of the optically active crystals—some examples are *D*- and DL-alanine, *D*- and DL-leucine, *D*- and DL-penillamine hydrochlorides. It is relatively seldom that the *D*- and the *L*-crystals separate, as in Pasteur's original experiments, but it happens occasionally, and has recently been

⁶⁴ Brown and Farthing, *Nature*, 1949, **164**, 915

⁶⁵ *Chem. Weekblad*, 1948, **44**, 217. ⁶⁶ *Ibid.*, p. 220.

⁶⁷ Clark, Kaye, Pipenberg, and Schieltz, "The Chemistry of Penicillin," Princeton Univ. Press, 1949, p. 367.

⁶⁸ Hinman, Caron, Louis, and Christenson, *J. Amer. Chem. Soc.*, 1950, **72**, 1620.

⁶⁹ Soldate and Noyes, *Analyt. Chem.*, 1947, **19**, 442.

⁷⁰ *J. Chem. Physics*, 1950, **18**, 757, 1035.

observed in the case of one form of β -phenylglyceric acid,⁷¹ tetrachlorocyclohexane, m. p. 174°, and threonine. Crystals of natural L-threonine are, for example, indistinguishable by X-ray methods from those in preparations of synthetic DL-threonine.

The number of organic compounds which we have to consider this year tempts us to draft this Report in the form of an outline text-book of organic chemistry, although sections of our text are still absent or very incomplete. Few measurements on organic compounds have yet been made at low temperatures, and the first members of most of the aliphatic homologous series are, therefore, still missing. These have, for the most part, been already examined by electron diffraction, and the series here described may be completed, so far as molecular structure is concerned, by reference to the very useful summary of electron-diffraction data given by Allen and Sutton in, significantly enough, *Acta Crystallographica*.⁷²

D. C. H.

Aliphatic Compounds.—Although they raise a number of other problems as well, the crystal structures in the first six classification groups below are concerned principally with the character and influence of long hydrocarbon chains. The way in which long-chain molecules fit into crystals has been approximately known for some time. But the accurate knowledge now obtained introduces detail that could not have been guessed, both in the arrangement and in the structure of the chains. The interest of the crystal structures in the later classification groups is rather different, partly stereochemical and partly concerned with the effect of active groups on crystal and molecular structure.

Hydrocarbons. The smallest hydrocarbon we have to mention is dimethyltriacetylene (octa-2 : 4 : 6-triyne),⁷³ which has a very simple crystal structure based on rod close packing, with one molecule in the rhombohedral unit cell. The bond lengths have been measured with good accuracy and are given in Fig. 4. They agree well with those in other acetylenes that have been recorded.

The zig-zag paraffin chain introduces crystallographic complications; the hydrocarbon $C_{18}H_{38}$ for example, of which preliminary measurements are given,⁷⁴ crystallises in a one-molecule triclinic cell. This is the low-temperature form. The higher-temperature modification, which is orthorhombic, has been re-examined for several hydrocarbons by Mazee⁷⁵ who finds that the a and b axes do not begin to change appreciably when the crystals are heated until a certain definite temperature is reached and that their ratio never quite reaches the hexagonal value that might be expected for fully rotating chains.

The mean atomic positions in very long hydrocarbons have been investigated in a new and most interesting way by Pinsker and others using

⁷¹ Furberg and Hassel, *Acta Chem. Scand.*, 1950, **4**, 1020.

⁷² *Ibid.*, 1950, **3**, 46.

⁷³ Jeffrey and Rollett, *Nature*, 1950, **166**, 475.

⁷⁴ Muller and Lonsdale, *Acta Cryst.*, 1948, **1**, 129.

⁷⁵ *Rec. Trav. chim.*, 1948, **67**, 197.

electron diffraction of the crystals.⁷⁶ A Fourier series formed, using the electron-structure amplitudes, gives a density function in which the maxima show the nuclear positions. Small peaks due to hydrogen atoms appear clearly visible and the mean bond dimensions are given as C—C 1.52, C—H 1.17 Å., \angle C—C—C 110°, \angle H—C—H 105°.

The very remarkable complexes formed by shaking straight-chain compounds with urea in the presence of a little solvent have been investigated by Smith who has proved that the complexes are of the clathrate type.⁷⁷

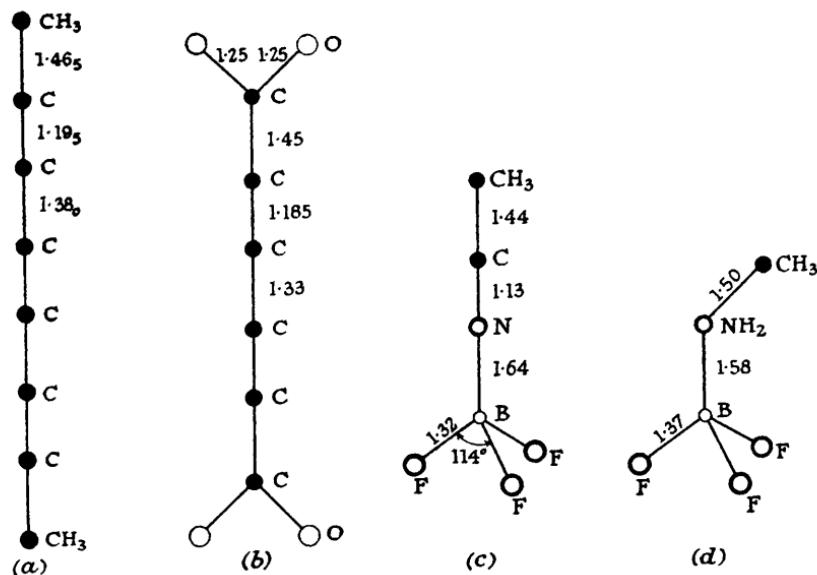


FIG. 4.

Interatomic distances in (a) dimethyltriacetylene (octa-2 : 4 : 6-triyne), (b) diacetylenedicarboxylic (butadienedicarboxylic) acid, (c) methyl cyanide–boron trifluoride, and (d) methylamine–boron trifluoride.

The urea molecules are arranged in a hexagonal unit cell on a spiral framework held together by hydrogen bonds. In the centre of the spiral lie the hydrocarbon chains, the plane of the zig-zag having a random distribution about three directions at 120° to one another. The parameters of the carbon atoms in the chain-length direction are not fixed unless it happens that this length is a near multiple of the urea repeating unit. Similar structures are formed with thiourea—the channels are wider here and branched-chain hydrocarbons or cyclohexane derivatives can be accommodated.

Alcohols and Esters. X-Ray diffraction effects observed for liquid ethyl alcohol suggest a gradual change as the temperature is lowered between association of the molecules in pairs at -75° and in chains in the super-

⁷⁶ Vainshtein and Pinsker, *Dokl. Akad. Nauk., S.S.S.R.*, 1950, **72**, 53; cf. Weinstein and Pinsker, *ibid.*, 1949, **64**, 49. ⁷⁷ *J. Chem. Physics*, 1950, **18**, 150.

cooled liquid at -150° .⁷⁸ No detailed structure analysis of a simple alcohol has, however, been reported and only preliminary measurements are given on higher-chain alcohols, such as the cetyl alcohols⁷⁹ and 9 : 10-epoxy-octadecanols.⁸⁰

An important ester structure described is that of pentaerythritol tetranitrate.⁸¹ The bond lengths found are recorded in Fig. 5a and are not as expected, particularly the short $\text{CH}_2\text{-O}$ bond of 1.37 Å. Dipole measurements suggest that this bond has little double-bond character, as far as effect on restriction of rotation is concerned.⁸² It is possible that the X-ray data are not yet sufficiently refined for the inter-atomic distances to be completely established, but it is at least suggestive that $\text{CH}_2\text{-O}$ shows

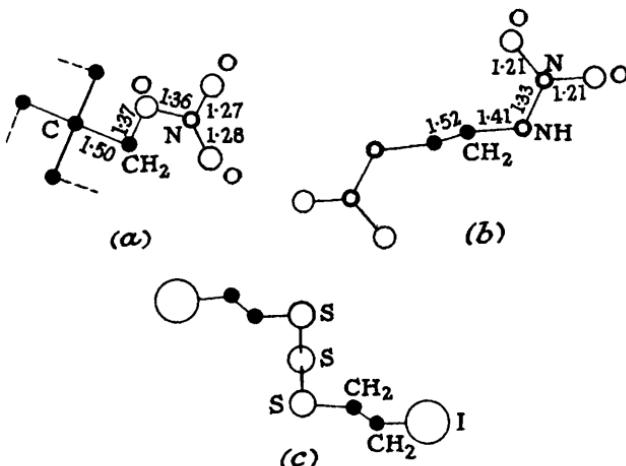


FIG. 5.

Interatomic distances in (a) pentaerythritol tetranitrate, (b) bisnitraminoethane, and (c) chain form in di-(2-iodoethyl) trisulphide.

a progressive change from 1.46 Å. in pentaerythritol⁸³ to 1.41 Å. in the tetra-acetate⁸⁴ and 1.37 Å. here; the explosive character of the compound also suggests that some abnormality might be present.

From among the huge volume of preliminary data recorded on long-chain esters and particularly glycerides, one may select for mention the fact that X-ray data have been used to show the identity of $(-)\alpha$ -(dipalmitoyl)-lecithin and the natural (dipalmitoyl)lecithin.⁸⁵

Alkyl Sulphides and Polysulphides. The most interesting feature of sulphur-containing chains appears to be their tendency—shown in plastic

⁷⁸ Jagodzinski, *Z. Naturforsch.*, 1947, **2a**, 465.

⁷⁹ Sano and Kakiuchi, *J. Phys. Soc., Japan*, 1949, **4**, 178.

⁸⁰ Witnauer and Swern, *J. Amer. Chem. Soc.*, 1950, **72**, 3365.

⁸¹ Booth and Llewellyn, *J.*, 1947, 837.

⁸² Springall and Spedding, *Research*, 1949, 295.

⁸³ Llewellyn, Cox, and Hardy, *J.*, 1937, 887.

⁸⁴ Goodwin and Hardy, *Proc. Roy. Soc.*, 1938, **A**, 164, 369.

⁸⁵ Baer and Kates, *J. Amer. Chem. Soc.*, 1950, **72**, 942.

sulphur and S₈ itself—not to conform to the planar zig-zag hydrocarbon type. Dawson and Robertson⁸⁶ were able to show that in di-(2-iodoethyl) trisulphide the sulphur atoms form an unbranched chain. Their arrangement of the carbon atoms has, however, been revised by Donohue who has given reasonably convincing evidence that the molecule as a whole has a twisted structure (Fig. 5c) with the dihedral angles S-S-S-C and S-S-C-C both close to 90° (cf. dimethyl trisulphide⁸⁷) and the group S-C-C-I coplanar and *trans*.⁸⁸

Amines, Alkylammonium Salts, and Nitroamines.—Methylamine itself may be taken as represented by the compound methylamine–boron trifluoride,⁸⁹ although the main interest here lies in the comparison of this compound with methyl cyanide–boron trifluoride⁹⁰ and the characteristics of the boron–nitrogen link. The bond distances in the methylamine and methyl cyanide parts of the molecules appear to be quite normal. But the B–N bond, the co-ordinate link, is long in both compounds, and the additional lengthening in the methyl cyanide compound is correlated both with a shortening of the B–F distance and increase in the angle F–B–F, and also with the decreased stability of the substance (Fig. 4c and d). The general arrangement of the atoms conforms to staggered packing, and the hydrogen atoms can be placed in the crystal.

With the next amine on the list, *n*-propylamine as hydrochloride, we have a crystal structure which caused some controversy many years ago until the possibility of chain rotation was recognised.⁹¹ In the room-temperature structure of *n*-propylammonium chloride, the cations have a disordered arrangement in relation to the tetragonal axis. They are taking part either in rotation, or in hindered rotation, about the chain axis as a whole and there seems also rotation about the central carbon–carbon bond with production of some of the “gauche” or twisted form of chain. At —80° to —90° there is an arrest of the cooling curve of the salt suggesting a second-order transition, disorder–order, in the solid. The diffraction spots become doubled, indicating break up of the crystal into domains of lower symmetry. Here the cations are fixed in the planar zig-zag form and lie in the (110) planes of the room-temperature structure, with consequent small changes in lattice constants and symmetry.

With hexamethylenediamine dihydrochloride⁹² and bromide,⁹³ we reach stable room-temperature structures with an intricately fitted together criss-cross arrangement of the chains. The molecules have a planar zig-zag form with the exception of the terminal C–NH bonds which lie 7–10° from the plane of the other atoms. This is almost certainly caused by the necessities of packing round the Cl ions, and hydrogen-bond formation with them, since in the very beautiful structure of hexamethylenediamine

⁸⁶ J., 1948, 1256. ⁸⁷ Donohue and Schomaker, *J. Chem. Physics*, 1948, **16**, 92.

⁸⁸ *J. Amer. Chem. Soc.*, 1950, **72**, 2701.

⁸⁹ Geller and Hoard, *Acta Cryst.*, 1950, **3**, 121.

⁹⁰ Hoard, Owen, Buzzell, and Salmon, *ibid.*, p. 130.

⁹¹ King and Lipscomb, *ibid.*, pp. 222, 227.

⁹² Binnie and Robertson, *ibid.*, 1949, **2**, 180. ⁹³ *Idem, ibid.*, p. 116.

itself the atoms are coplanar throughout.⁹⁴ In both structures there appears to be an alternation in the bond lengths along the chain (Fig. 6), suggesting hyperconjugation, and the angles within the chain are generally slightly greater than the tetrahedral. Again hydrogen atoms appear in the electron-density projection.

With amine salts having much longer chains, such as the stearyl- and palmitoyl-choline salts, of which very approximate electron-density projections have been calculated,⁹⁵ the molecular arrangement conforms more closely to the ionic double layer-parallel chain type.

The two nitramines studied have little relation to the other compounds in this group. The molecular structures are dominated by the nitro-group. In dimethylnitramine, all the atoms lie in one plane;⁹⁶ in *s*-bisnitramino-

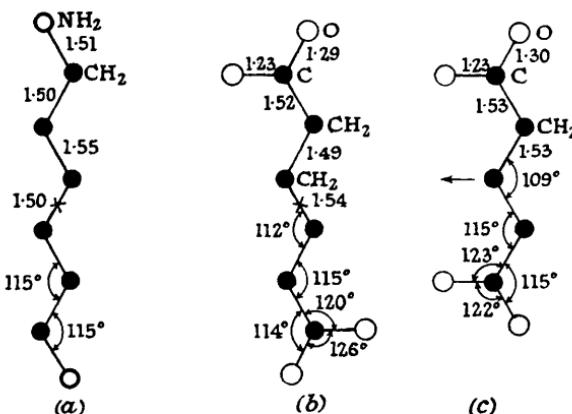


FIG. 6.

Interatomic distances in (a) hexamethylenediamine, (b) adipic acid, and (c) glutaric acid.

ethane,⁹⁷ the half molecule $\text{CH}_2\text{-NH-NO}_2$ is nearly planar. In both, the N-N bond is considerably shorter than the normal single bond distance (Fig. 5b).

Monobasic Acids and their Salts. In view of the enormous volume of work published on long-chain acids and their salts, one is particularly grateful for the first detailed analyses of some of these compounds, potassium hexanoate (caproate)⁵⁴ and strontium laurate.⁹⁸ In both compounds the aliphatic chains have the planar zig-zag structure and the slightly long carbon-carbon repeat interval $2\cdot59_3 - 2\cdot60_5$ Å. along the chain agrees well with that in other structures where the $\angle \text{C-C-C}$ is about 115° and C-C about 1.54 Å. In potassium decanoate, the potassium ions are arranged in a double layer, each surrounded by six carboxyl oxygens, four from two chains on one side,

⁹⁴ Binnie and Robertson, *Acta Cryst.*, 1949, **2**, 424.

⁹⁵ Stora, *Compt. rend.*, 1949, **228**, 324; **229**, 874; 1950, **230**, 1675.

⁹⁶ Costain and Cox, *Nature*, 1947, **160**, 826.

⁹⁷ Llewellyn and Whitmore, *J.*, 1948, 1316.

⁹⁸ Morley and Vand, *Nature*, 1949, **163**, 284.

two from one chain on the other. But within a single decanoate layer, bounded by the ions, the molecules form further layers in which the chain directions are crossed to one another at angles of about 60° . In such a structure, it is not surprising that frequent faults occur in the regular arrangement of the molecules.

Measurements of unit cell dimensions have been reported for a number of other fatty acid salts and acids⁹⁹ and it is to be hoped that some of the other structure types reported will soon be known in detail. One interesting possibility has been proposed for aluminium monolaurate¹⁰⁰—that there are oxygen octahedra present similar to those in alumina, joined by sharing of two corners, the carboxyl oxygen atoms occupying the remaining four corners of each octahedron.

The appearance, in natural products, of a number of long-chain compounds with small branched chains, such as tuberculostearic acid, ($-$)-10-methyloctadecanoic acid¹⁰¹ and phthiocerane, which is mainly (\pm)-4-methyltristriaccontane,¹⁰² has led to a good many X-ray measurements of their different crystalline forms. Usually the compounds show marked similarities with the normal straight-chain derivatives; in the case of one series of amides, Velick¹⁰³ noticed marked deviations, which he suggested might be correlated with the appearance of a spiral-chain configuration. However, later observations indicate the occurrence of different crystalline modifications here.¹⁰⁴ While therefore a spiral carbon-chain structure remains still to be found, definite distortions from the planar zig-zag-chain form do occur in the next group of compounds, the dibasic acids.

Dibasic Acids. As a result, principally, of two independent series of researches carried out in Holland and at Glasgow, we can now consider details of the crystal structures of six different straight-chain dibasic acids in the interval oxalic to sebacic acid. These are particularly interesting in relation to the marked alternation in physical properties which occurs between acids of the odd and the even series.

As might be expected, the early members of both series, oxalic, malonic, and succinic acids, show deviations from the types of crystal structure characteristics of the higher members. Oxalic acid itself crystallises in three different modifications, α - and β -oxalic acid which are both anhydrous,¹⁰⁵ and the dihydrate. Of these, the α -form is unique in that the molecules are linked in sheets by hydrogen bonds between the oxygen atoms of one carboxyl group and two other carboxyl groups. Malonic acid has not yet

⁹⁹ Iball, *Nature*, 1947, **159**, 95; Vand, *Acta Cryst.*, 1948, **1**, 109; Vand, Aitken, and Campbell, *ibid.*, 1949, **1**, 398; Lingafelter and Jensen, *ibid.*, 1950, **3**, 257; Minor and Lingafelter, *J. Amer. Chem. Soc.*, 1949, **71**, 1145; Witnauer, Lee, and Senti, *ibid.*, 1950, **72**, 283; Kohlhaas, *Ber.*, 1949, **82**, 487.

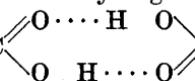
¹⁰⁰ McGee, *J. Amer. Chem. Soc.*, 1949, **71**, 278.

¹⁰¹ S. Stallberg-Stenhagen, *Arkiv Kemi, Min., Geol.*, 1948, **26**, A, No. 12.

¹⁰² S. Stallberg-Stenhagen and E. Stenhagen, *J. Biol. Chem.*, 1948, **173**, 383; 1950, **183**, 223. ¹⁰³ *J. Amer. Chem. Soc.*, 1947, **69**, 2317.

¹⁰⁴ Arosenius, Stallberg, E. Stenhagen, and B. Tagstrom-Eketorp, *Arkiv Kemi, Min., Geol.*, 1948, **26**, A, No. 19. ¹⁰⁵ Hendricks, *Z. Krist.*, 1935, **91**, 48.

been studied in detail; only cell dimensions are recorded for the different varieties. In all the other crystal structures found, the molecules are linked in chains with the carboxyl groups of succeeding molecules joined end to end through hydrogen bonds. In the dihydrates, the water molecules are inserted into the hydrogen-bond system; in all the others, the

form of the group  is remarkably constant, whatever the rest of the crystal structure may be like, with $O \cdots O$ contacts of 2.64—2.69 Å.

The even acids, adipic¹⁰⁶ and sebacic acid,¹⁰⁷ are characterised by a simple monoclinic crystal structure in which the molecules are centrosymmetrical. The atoms have a nearly planar zig-zag arrangement throughout the length of the molecule: in adipic acid the atoms of the carboxyl group lie in a plane tilted about 6° from the plane of the other atoms; in sebacic acid this tilt is only 3°, in β-succinic acid 9°.¹⁰⁸ The α- and the β-form of succinic acid differ from the higher members chiefly in the relative arrangement of the molecules normal to the chain, the triclinic α-form approximating most closely to the packing shown by the higher numbers.¹⁰⁹

The most obvious difference in the crystal structures of the acids of the odd series, glutaric^{110, 111} and pimelic acid¹¹¹ is that the molecules are no longer nearly planar, but have a twisted form; even the carbon atoms do not lie strictly in one plane, and the terminal carboxyl groups lie in two planes at about 60° to one another and 30° to the plane of the centre three carbon atoms. As a whole, the molecules have a two-fold axis of symmetry, a centre of symmetry being, of course, impossible. It seems very probable, from calculations carried out by MacGillavry *et al.*, that the twisted form of the molecule is responsible for the extra energy content of crystals in the odd series. The potential barrier to rotation in acetone, *ca.* 1 kcal., suggests that the extra energy in the odd series molecules would be of the order of 2 kcals., a difference which corresponds in magnitude to observed differences in the heats of combustion. Morrison and Robertson make two observations: first, that there is a tendency to alternation in the carbon-carbon bond lengths along the hydrocarbon chains in the even series and no such effect in glutaric acid (Fig. 6); this may be correlated with the molecular twisting; and, secondly, that one very short contact, 3.29 Å., occurs between an oxygen and a carbon atom of neighbouring molecules in adipic and sebacic acids and not in glutaric acid; this may also affect the melting point and hardness of the crystals. We have the impression that the hydrogen-bond system is the dominating factor in determining the crystal structures, molecular compression or distortion occurring as necessary to fit this with particular conditions of molecular shape.

¹⁰⁶ MacGillavry, *Rec. Trav. chim.*, 1941, **60**, 605; Morrison and Robertson, *J.*, 1949, 987.

¹⁰⁷ *Idem, ibid.*, p. 993.

¹⁰⁸ *Idem, ibid.*, p. 980.

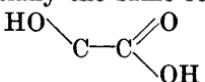
¹⁰⁹ Riech, *Rec. Trav. chim.*, 1944, **63**, 170. ¹¹⁰ Morrison and Robertson, *J.*, 1949, 1001.

¹¹¹ MacGillavry, Hoogschagen, and Sixma, *Rec. Trav. chim.*, 1948, **67**, 869.

Another series of acids is the series formed by oxalic acid dihydrate¹¹² and acetylene-¹¹³ and butadiyne (diacetylene)-dicarboxylic acid dihydrates.¹¹⁴ The system by which two succeeding carboxyl groups are linked in a chain through the water molecules is the same in all three crystals; all show the very short hydrogen bond, 2.51—2.56 Å., between one carboxyl-oxygen atom and the water molecule, here probably an oxonium ion. The system holds in spite of the fact that oxalic and acetylenedicarboxylic acid are essentially planar and centrosymmetrical molecules, while butadiyne-dicarboxylic acid has, like the odd acid series above, a two-fold axis of symmetry and carboxyl groups turned in two planes at an angle of 57° to one another. The evidence on the bond distances within the oxalic acid molecule itself has been reviewed by Dunitz and Robertson;¹¹² their preferred values may still have to be modified further after three-dimensional analysis. The figures for bond lengths in the acetylenic chains ought to be less liable to change; the most remarkable bond length here is the central bond length in the diacetylenic acid, the shortest formal single carbon-carbon link so far recorded, 1.33 ± 0.02 Å. In this molecule, however, the contraction of the bond lengths does not appear to be correlated with decreased freedom of rotation, if the relative arrangement is taken as evidence—compare the situation in pentaerythritol tetranitrate discussed above.

Hydroxy-acids : the Tartrates. To the crystal structure of Rochelle salt,¹¹⁵ sodium potassium tartrate tetrahydrate, we can now add those of sodium potassium DL-tartrate tetrahydrate,¹¹⁶ D₂-tartric acid,¹¹⁷ and racemic acid,¹¹⁸ a group of crystals interesting on account both of Pasteur's original work on molecular asymmetry and also of the electrical properties of Rochelle salt.

In all four crystal structures the asymmetric tartaric acid molecule maintains essentially the same relative arrangement of the atoms present :

the two groups  are both closely planar and are arranged

with their planes at an angle of approximately 60° to one another. There is a certain similarity between the packing of the molecules in the two salts, which is partly controlled by the requirements of the ions. The differences introduced by the centre of symmetry and the changed hydroxyl-group relations in the crystal of the racemate are however enough to destroy the unidirectional series of hydrogen bonds found in Rochelle salt, and hence the development of abnormal electric properties. The relation between the exact atomic positions and these properties in the Rochelle salt crystal is in any case very sensitive, as illustrated by the correlation found by Ubbelohde and Woodward between the thermal expansion and the dielectric

¹¹² Dunitz and Robertson, *J.*, 1947, 142.

¹¹³ *Idem, ibid.*, p. 148.

¹¹⁴ *Idem, ibid.*, p. 1145.

¹¹⁵ Beevers and Hughes, *Proc. Roy. Soc.*, 1941, A, 177, 251.

¹¹⁶ Sadanaga, *Acta Cryst.*, 1950, 3, 416.

¹¹⁷ Stern and Beevers, *ibid.*, p. 341. ¹¹⁸ Parry, *Nature*, 1949, 164, 885.

constant of the crystal,¹¹⁹ and also by the effect of altering the proportions of the ions in the crystals.¹²⁰ The view that the crystal between the two Curie points consists of domains of lower symmetry has received some additional confirmation from measurements on the integrated intensity of X-ray reflections.¹²¹ These are higher between the Curie points than above them, as might be expected from the imperfect kind of crystal formed. Changes in the size and nature of the domains might account for the marked effect that certain impurities such as cupric ion and boric acid also have on the electric properties of crystals grown in their presence.

The differences between the crystal structures of D-tartaric and racemic acid are pronounced. In the racemic acid crystal unit there are only two molecules related by a crystallographic centre of symmetry. But, as expected, there is no definite pair association of D- and L-units, no racemic acid molecule present, but an over-all hydrogen-bond system holding the molecules in the crystal. Parallel to the *a* axis, columns of D- and L-molecules are connected by a square system of hydrogen bonds between the hydroxyl groups. End to end, D- and L-molecules are also linked through one pair of carboxyl groups as in the other dibasic acids described. The second carboxyl group in each case makes contacts with both carboxyl- and hydroxyl-oxygen atoms of neighbouring molecules. In D-tartaric acid, the system of hydrogen bonding is necessarily different from that in racemic acid. The two molecules in the unit are related by a screw axis of symmetry and in this crystal structure there is no pairing of carboxyl groups of neighbouring molecules of the dibasic acid type. Instead a more complex linking of carboxyl groups with hydroxyl groups is present.

One particularly interesting point about the D-tartaric acid crystal structure is that correlation of the molecular arrangement found with the face development of the crystals would permit a determination of the absolute configuration of the molecule. This has been attempted by Waser,¹²² but it is doubtful whether our knowledge of the factors affecting crystal growth is sufficient to feel complete confidence in his assignment¹²³—which is the exact opposite of Fischer's assumed arrangement.

Amino-acids and Peptides. The X-ray analysis of the amino-acid L_s-threonine³⁸ establishes unambiguously the stereochemical relation between the sugar-lactic acid and the amino-acid series.¹²⁴ The relation is the one derived as most probable by the original observations of Meyer and Rose,¹²⁵ following the first isolation of threonine, and recently independently established through kinetically-controlled chemical reactions.¹²⁶ It is shown in Fig. 7 by a perspective drawing of the threonine molecule, which illustrates both the arrangement of the atoms and the bond lengths within the molecule.

¹¹⁹ Proc. Roy. Soc., 1946, A, **185**, 448.

¹²⁰ Thorp and Buckley, Acta Cryst., 1949, **2**, 333.

¹²¹ Mujake, *ibid.*, p. 192. ¹²² J. Chem. Physics, 1949, **17**, 498.

¹²³ Turner and Lonsdale, J. Chem. Physics, 1950, **18**, 156.

¹²⁴ Cf. Neuberger, Adv. Protein Chem., 1948, **4**, 297.

¹²⁵ J. Biol. Chem., 1936, **115**, 721.

¹²⁶ Brewster, Hughes, Ingold, and Rao, Nature, 1950, **166**, 178.

The crystallographic investigation of threonine constitutes the most comprehensive and thorough study yet undertaken of an asymmetric molecule and provides a fund of useful information on the technique of crystal analysis. The full, three-dimensional electron-density distribution has been calculated six times in the course of refinement—until recently a single such calculation would have been considered to involve an impossible amount of labour. The electron-density distribution shows the positions of hydrogen atoms as separate, but not very precise, maxima, and enables the positions of all the remaining atoms to be fixed with a high degree of

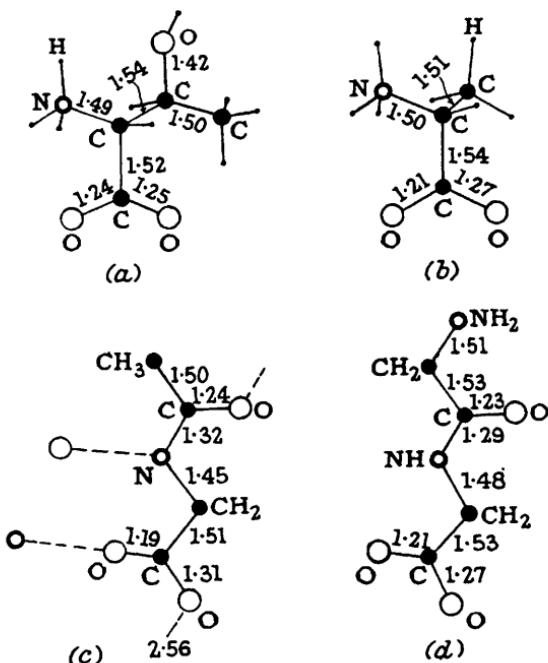


FIG. 7.
Interatomic distances in (a) threonine, (b) alanine,
(c) acetylglycine, and (d) β -glycylglycine.

precision. The C–N distance, 1.49 Å., is close to that expected from the sum of the covalent radii, and it is clear that the short values reported earlier for glycine and alanine¹²⁷ were based on insufficient refinement of the data. Both have been found to be normal from recent three-dimensional analyses.

Within the threonine molecule it is noticeable that the staggered arrangement of the atoms is very precisely observed, so that the contacts between non-bonded atoms are of the most favourable form—even to placing the hydrogen of C₃, in the gap between NH₃⁺ and CO₂[−] rather than the larger OH and CH₃ groups. At the same time, a high density of packing of the molecules in the crystal is achieved with all the hydrogen atoms of the

¹²⁷ Donohue, *J. Amer. Chem. Soc.*, 1950, **72**, 949.

NH_3^+ and OH groups involved in hydrogen bonding. It is clear from the distribution found for the hydrogen atoms that the molecule has the zwitter-ion structure. There is one comparatively short distance, 3.28 Å., between one carbon atom and the hydroxyl group.

The analyses of other amino-acids reported as begun during these years—glycylglycine hydrobromide,¹²⁸ DL- and L-leucine,¹²⁹ and L-proline¹³⁰—have not yet reached the stage at which interatomic distances can be given. But two analyses, those of acetylglycine¹³¹ and of β-glycylglycine,¹³² provide a useful basis for the theoretical construction of extended peptide chains.¹³³ Both molecules are planar or very nearly so; in glycylglycine the terminal nitrogen atom only is out of the plane of the other atoms. It is noticeable that the C—O distances in the acetylglycine carboxyl group, which has no zwitter-ion character, are markedly asymmetric, corresponding to not greatly modified C=O and C—OH distances. Apart from this, the crystal structures have considerable similarity; in both, the molecules are linked in sheets by hydrogen bonds between carboxyl, keto-, amino-, or imino-groups. In both, one can see a formal relationship to the extended β-form of peptide-chain structure, though the sideways linking in one case involves CO₂H and NH groups, in the other case C=O and NH₂, and in neither case the postulated C=O ··· NH bonds of the β-keratin structure.

Structures in which the C=O ··· NH linking occurs are, however, well established by the work of Bunn and Garner and others on certain polyamides.¹³⁴ These are fibres and give only limited X-ray diffraction data;¹³⁵ consequently the position of the atoms cannot be very precisely fixed. But they are sufficiently clear to prove that here too the molecules are held in sheets, the oxygen-nitrogen separation of neighbouring molecules within the sheets being 2.8 Å. The sheet thickness, 4.4 Å., compares very well with the backbone spacing of the β-keratin type of fibrous protein.

Alicyclic Ring Systems. With the alicyclic ring compounds stereochemical problems are again dominant. Few of the X-ray analyses in this series are sufficiently accurate for the interatomic distances found to be worth reporting, but there are one or two interesting exceptions.

No cyclopropane derivative has yet been analysed in detail by X-ray methods. For completeness, we may quote Skinner's conclusion¹³⁶ that the ring-carbon atoms are arranged in a regular equilateral triangle of side rather smaller than 1.54 Å., in accordance with certain quantum-mechanical calculations.

In all the cyclobutane derivatives studied on the other hand, the carbon-carbon distance has proved, unexpectedly, greater than normal. The most careful analysis is that of the centrosymmetrical isomer of 1:2:3:4-

¹²⁸ Barney, *Amer. Min.*, 1947, 685. ¹²⁹ Möller, *Acta Chem. Scand.*, 1949, **3**, 1326.

¹³⁰ Wright and Cole, *Acta Cryst.*, 1949, **2**, 129.

¹³¹ Carpenter and Donohue, *J. Amer. Chem. Soc.*, 1950, **72**, 2315.

¹³² Hughes and Moore, *ibid.*, 1949, **71**, 2618.

¹³³ Corey and Donohue, *ibid.*, 1950, **72**, 2899. ¹³⁴ *Proc. Roy. Soc.*, 1947, **A, 189**, 39.

¹³⁵ Beauvalet, Champetier, and Tertian, *Compt. rend.*, 1949, **228**, 2028.

¹³⁶ *Nature*, 1947, **160**, 902.

tetraphenylcyclobutane,⁶³ which is formed by the photochemical dimerisation of stilbene. The analysis of this compound was undertaken, in the first instance, to establish the nature of the toxic irradiation-product of the drug "Stilbamidine," from which it had been obtained. The crystal structure showed both that the four-membered ring was present, and that the phenyl groups were disposed centrosymmetrically round it. As a result, this arrangement is different in relation to the two adjacent bonds in the four-membered ring alternately, *cis* and *trans*, which may account for the fact that these bonds appear to be of unequal length, 1.585 and 1.555 Å. respectively.

The other X-ray analysis of a four-membered ring derivative, that of the centrosymmetrical dimer of acenaphthylene,¹³⁷ is not complete, but it too shows bonds in the ring which are longer than 1.54 Å. Bond lengthening also appears very markedly from the electron-diffraction data on octafluorocyclobutane,¹³⁸ for which the carbon-carbon distance in the ring is given as 1.57—1.62 Å. and the ring appears to be non-planar. The lengthening of the bond is probably correlated with a greater proportion of p-bond character, the angle between the C-C valencies in the ring being nearly 90°. Repulsion between non-bonded atoms must also have an effect.

Certainly with five- and six-membered rings, it is clear that the packing of non-bonded atoms plays a dominant part in determining their overall arrangement. The five-membered carbon rings so far observed are all non-planar, usually with one atom out of a plane formed by the other four. They include the five-membered rings in bromo-, chloro-, and cyano-camphor¹³⁹ and ring D of cholesteryl iodide¹⁴⁰ and calciferol 4-iodo-5-nitrobenzoate.¹⁴¹ In almost all cyclohexane derivatives so far studied, including the *cis*-decalins, the ring has the staggered or chair form. Only in the camphor derivatives mentioned does the boat form appear, imposed by the fusion with five-membered rings. In 1:2-epoxycyclohexane,¹⁴² ring fusion again imposes a constraint but the atomic arrangement found by electron diffraction is still approximately staggered.

The simpler derivatives of cyclohexane, the hydrocarbon itself,¹⁴³ cyclohexanol,¹⁴⁴ and dodecafluorocyclohexane,¹⁴⁵ crystallise in cubic cells in which the molecular arrangement is considerably disordered. The molecules appear not to be freely rotating, but to have certain preferred orientations in relation to their neighbours.¹⁴⁶ With additional hydroxyl groups attached, the cyclohexane molecule can be readily held in a fixed position. Particularly good examples are provided by α-phloroglucitol dihydrate⁵⁸ and diammoniate.⁵⁹ The molecules have trigonal symmetry, which

¹³⁷ Dunitz and Weissman, *Acta Cryst.*, 1949, **2**, 62.

¹³⁸ Lemaire and Livingston, *J. Chem. Physics*, 1950, **18**, 569.

¹³⁹ Wiebenga and Krom, *Rec. Trav. chim.*, 1946, **65**, 663.

¹⁴⁰ Carlisle and Crowfoot, *Proc. Roy. Soc.*, 1945, **A**, **184**, 64.

¹⁴¹ Crowfoot and Dunitz, *Nature*, 1948, **162**, 608.

¹⁴² Otter, *Acta Chem. Scand.*, 1947, **1**, 283.

¹⁴³ Oda, *X-Rays*, 1948, **5**, 26. ¹⁴⁴ Oda, *ibid.*, 1949, **5**, 95.

¹⁴⁵ Christoffers, Lingafelter, and Cady, *J. Amer. Chem. Soc.*, 1947, **69**, 2502.

¹⁴⁶ King and Lipscomb, *Acta Cryst.*, 1950, **3**, 155.

establishes their stereochemical form (Fig. 8), and are linked in threes round water or ammonia molecules which form a fourth bond between one another.

It is difficult to summarise adequately the crystal analyses of the very interesting group of different halogenated cyclohexanes—all of which involve the determination of the nature of the stereochemical isomer present, and in two cases, those of the hexachlorocyclohexane, m. p. 145°,¹⁴⁷ and tetrachlorocyclohexane, m. p. 174°, the carbon atoms to which the chlorine atoms were attached. "Gammexane,"¹⁴⁸ as an insecticide, is the most important of these compounds. The molecule proves to have the structure shown in Fig. 8, which was unexpected since it had been supposed that steric hindrance might prevent altogether the formation of the isomer with chlorine atoms at 1 and 3 both in the erect position. There is a slight distortion of the molecule as a result—the bonds C₍₁₎—Cl and C₍₃₎—Cl are not quite parallel, but the distortion is small. The same problem does not arise in the case of the other isomers studied, *viz.*, 8.¹⁴⁹ and ε-hexachlorocyclohexane,¹⁵⁰ though all show small deviations from the quite regular form of the molecules indicated in Fig. 8, which all should have planes of symmetry. 1:2:4:5-Tetrachlorocyclohexane, m. p. 174°, and 1:2:3:4-tetrabromocyclohexane, m. p. 142°, both have two-fold axes of symmetry;¹⁵¹ in the first case it should be possible to separate the crystals by hand into (+)- and (-)-forms. Actually one polymorphic modification of 1:2:4:5-tetrabromocyclohexane, m. p. 218°, was picked out by hand from a mixture of crystals and the molecule proved by X-ray analysis to have the structure given in Fig. 8.¹⁵²

Rings in which methylene groups have been replaced by oxygen atoms or imino-groups have not been so fully investigated but appear from the few known examples to have similar stereochemical characteristics. These examples include di-iodomethyloxacyclobutane,¹⁵³ the furanose and pyranose rings of the sugars discussed in the next section, and 1:4-dichloropiperazine.¹⁵⁴ It should be possible to get really good measurements from di-1:3-dioxacyclopentyl,¹⁵⁵ the chemical structure of which was found by the calculation of a Fourier projection from data on crystals which had been supposed previously to be a *cis*-decalin type of isomer of naphthodioxan.

Carbohydrates. The crystal structures of three sugars have recently been analysed or partly analysed: α-D-glucose,¹⁵⁶ difructose strontium

¹⁴⁷ Ellefsen, Hassel, and Wang Lund, *Acta Chem. Scand.*, 1950, **4**, 1145.

¹⁴⁸ van Vloten, Kruissink, Strijk, and Bijvoet, *Acta Cryst.*, 1950, **3**, 139; *Nature*, 1948, **162**, 771; *Rec. Trav. chim.*, 1948, **67**, 777.

¹⁴⁹ van Bommel, Strijk, and Bijvoet, *Proc. K. Akad. Wetensch.*, 1950, **53**, 50.

¹⁵⁰ Norman, *Acta Chem. Scand.*, 1950, **4**, 251.

¹⁵¹ Hassel and Wang Lund, *ibid.*, 1949, **3**, 203; *Acta Cryst.*, 1949, **2**, 309; Wang Lund, *Acta Chem. Scand.*, 1950, **4**, 1109.

¹⁵² Haak, Thesis "De berciding en structuur van cyclohexadien-1, 4 en van enige derivaten," P. Harte, Bergen op Zoom, 1948.

¹⁵³ Toussaint, *Bull. Soc. roy. Sci. Liège*, 1948, **1**, 18.

¹⁵⁴ Anderson and Hassel, *Acta Chem. Scand.*, 1949, **3**, 1180.

¹⁵⁵ Dano, Furberg, and Hassel, *ibid.*, 1950, **4**, 965.

¹⁵⁶ McDonald and Beevers, *Acta Cryst.*, 1950, **3**, 394.

chloride trihydrate,¹⁵⁷ and sucrose sodium bromide dihydrate.¹⁵⁸ The determination of the structure of α -D-ribofuranose is also involved in the analysis of cytidine.¹⁵⁹ In all cases the stereochemical arrangement of the hydroxyl groups, predicted on chemical grounds, is confirmed. This includes the *cis*-arrangement of the 1- and the 2-hydroxyl group in the two α -glucose units.

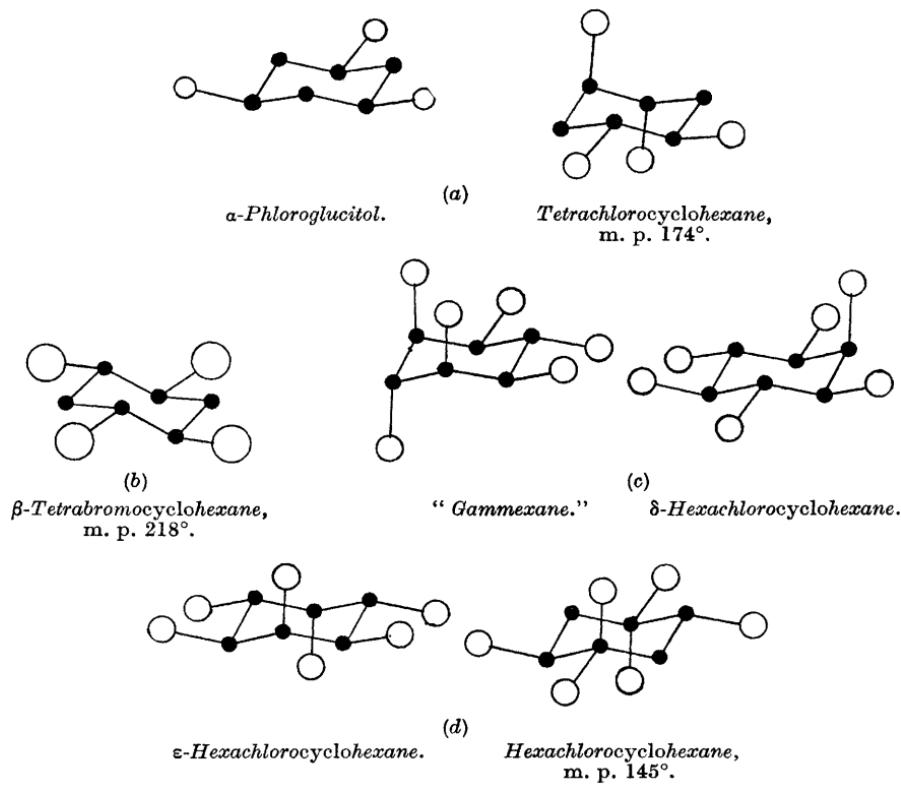


FIG. 8.
Stereochemical form of some substituted cyclohexane derivatives.

Both the glucose ring and also the fructose ring in the strontium chloride complex are six-membered in the Sachse *trans*-configuration. In sucrose the fructose ring is five-membered as expected, and non-planar, one carbon atom being removed from the plane of the other four. Bond lengths are not accurately determined in any of these compounds, but the α -D-glucose crystal structure is being further refined and should provide a good set of measurements. All the hydroxyl groups in both this and the sucrose structure are involved in hydrogen-bond formation. In α -D-glucose, as

¹⁵⁷ Eiland and Pepinsky, *Acta Cryst.*, 1950, **3**, 160.

¹⁵⁸ Beevers and Cochran, *Proc. Roy. Soc.*, 1947, **A**, 190, 257.

¹⁵⁹ Furberg, *Acta Cryst.*, 1950, **3**, 325.

in cytidine, the ring-oxygen atom itself appears to be bonded to the hydroxyl group of a neighbouring molecule.

A consideration of the stereochemical conditions obtaining in pyranose and in cyclohexane rings has led Hassel and Otter to suggest a new way of linking β -glucose units in a chain with an 8.5-A. period¹⁶⁰ that may correspond to the arrangement in many natural polymers, such as alginic acid, which show periods of this kind. This arrangement seems more probable than that put forward originally by Astbury.¹⁶¹ For cellulose itself, in spite of much controversy, the structure proposed by Meyer and Misch still seems the most likely.¹⁶² A three-fold spiral arrangement is suggested by the cell dimensions found for cyanoethyl cellulose.¹⁶³

More complicated unit cells are found among starches, and various tentative structures involving helical arrangements of the molecules have been proposed for different forms.¹⁶⁴ The variety known as V-amyllose, starch, or amylose precipitated from alcohol forms a lattice which suggests that the glucose residues are arranged in a six-fold helix of external diameter roughly 17 Å. and height 7.9 Å., and this idea receives some confirmation from an exceedingly rough Fourier projection derived by comparison with the iodine complex.¹⁶⁵ The iodine fits into the column surrounded by the helix, and observations by West suggest that the iodine molecules dissociate;¹⁶⁶ characteristic diffuse layer lines appear indicating a layer interval of 3.1 Å. in the direction of the iodine column.

The very interesting Schardinger dextrans form true crystalline lattices from which the molecular weights of the units present may be calculated in the usual way. They correspond to six, seven, and eight glucose residues respectively for α -, β -, and γ -Schardinger dextrans;¹⁶⁷ more than one polymorphic modification appears to exist for the α - and the β -dextrans.

D. C. H.

Aromatic Compounds.—The structures of aromatic compounds have for some time been studied very largely because they provide a wide variety of examples of bonds the characters of which are intermediate between single and double. This applies not only within the ring systems, but also in the bonds from the rings to substituting atoms or groups, and in the latter instance in particular has a bearing on the chemical reactivity of the substituents. While earlier work was of interest in indicating qualitatively these variations of bond length, it is only in the past few years that advances in crystallographic computing methods, and in the theoretical methods of calcu-

¹⁶⁰ *Acta Chem. Scand.*, 1947, **1**, 929. ¹⁶¹ *Nature*, 1945, **155**, 667.

¹⁶² van der Wyk and Meyer, *J. Polymer Sci.*, 1947, **2**, 583.

¹⁶³ Happey and MacGregor, *Nature*, 1947, **160**, 907.

¹⁶⁴ Kreger, *ibid.*, p. 369; Rundle, *ibid.*, 1948, **162**, 107; Senti and Witnauer, *J. Amer. Chem. Soc.*, 1948, **70**, 1438. ¹⁶⁵ Rundle, *ibid.*, 1947, **69**, 1769.

¹⁶⁶ *J. Chem. Physics*, 1947, **15**, 689; cf. Rundle, *ibid.*, p. 880.

¹⁶⁷ Borchert, *Z. Naturforsch.*, 1948, **3b**, 464; cf. Gruenhut, Cushing, and Caesar, *J. Amer. Chem. Soc.*, 1948, **70**, 424.

lating bond characters and bond lengths, have made possible a detailed comparison of experiment and theory. The calculations on both sides are even now very long and arduous, so that a full correlation can be expected only for a relatively small number of compounds. This correlation has been achieved for a few of the compounds discussed below, but in many of the other cases there are fresh indications of the occurrence of bonds of intermediate character.

Carbocyclic Compounds.—(a) *Hydrocarbons.* Naphthalene and anthracene were among the first organic crystals to be analysed by X-ray methods, and the recent full three-dimensional analyses (Fig. 3) by Robertson and his co-workers^{39,40} are of particular interest in confirming and extending the previous findings. The bond lengths found are shown in Fig. 9, and the correlation between the chemical reactivity of the α - β -bonds and their relative shortness is immediately apparent. The authors claim that errors in these bond lengths should not exceed 0.01 Å., and they observe that bonds

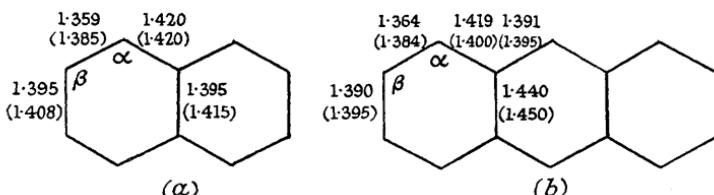


FIG. 9.

Aromatic hydrocarbons : (a) naphthalene ; (b) anthracene. Observed and calculated (parentheses) bond lengths are shown.

which are crystallographically different but chemically identical have lengths which differ by about 0.01 Å. This however raises the difficult question of the distortions caused by the packing of molecules in a crystal lattice, which appear to be noticeable in certain cases where observations of both the crystal and the vapour have been made. It may be pointed out that no correction has as yet been applied for series-termination errors.

Superposition of the simple Kekulé-type structures is insufficient in the cases of naphthalene and anthracene to explain the observed bond lengths, but it is now recognised that the contributions of the excited states must be included if a quantitative estimate is to be made. The bond lengths from some recent wave-mechanical calculations^{168,169} are shown in parentheses in Fig. 9.

Further investigations by two-dimensional Fourier methods have been reported on pyrene (I),¹⁷⁰ 1 : 2.5 : 6-dibenzanthracene (II),¹⁷¹ 1 : 12-benzperylene (III),¹⁷² ovalene (octabenzonaphthalene) (IV),¹⁷³ and triphenyl-

¹⁶⁸ Vroelant and Daudel, *Compt. rend.*, 1949, **228**, 399.

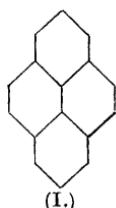
¹⁶⁹ Daudel and Daudel, *J. Chem. Physics*, 1948, **16**, 639.

¹⁷⁰ Robertson and White, *J.*, 1947, 358.

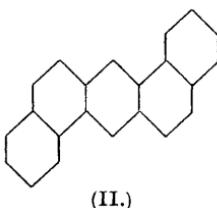
¹⁷¹ *Idem, ibid.*, p. 1001. ¹⁷² White, *J.*, 1948, 1398.

¹⁷³ Donaldson and Robertson, *Nature*, 1949, **164**, 1002.

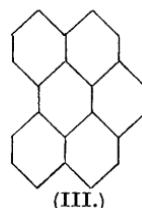
ene (V),¹⁷⁴ and in all cases bond lengths of intermediate character have been found. It would be unreasonable to expect very close correlation between



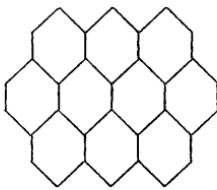
(I.)



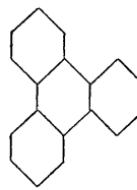
(II.)



(III.)



(IV.)



(V.)

these experimental measurements and the results of calculations based on the simple non-excited Kekulé structures, but in fact in a number of instances there is quite good qualitative agreement. This sometimes improves slightly if the contributions of the various Kekulé structures are weighted according to their benzenoid character, lending support to the Fries rule that structures with benzenoid rings are more important than those with quinonoid rings.¹⁷⁵

Another modification of hexamethylbenzene has been reported, stable between 110° and the melting point (165°).¹⁷⁶ It is more symmetrical than the form stable at ordinary temperatures but very closely related to it. The lattice energy and thermal expansion have been discussed by Seki and Chihara.¹⁷⁷

(b) *Benzene derivatives : halogen compounds.* The sequence of compounds, *p*-dichloro-, *p*-bromochloro-, *p*-dibromo-benzene, was first shown by Hendricks to be isomorphous. More recent work¹⁷⁸ has verified that the bromochloro-compound has a statistical structure, the chlorine and bromine atoms occupying two sets of crystallographically different positions at random. The bonds from the benzene ring appear equal, 1.77 Å., a value intermediate between that for C–Cl (1.69) found in the dichloro-compound and that for C–Br (1.84, 1.88) in the dibromo-compound. In *p*-chloroiodoxybenzene¹⁷⁹ the IO₂ plane is almost at right angles to the benzene ring, the O–I–O angle being 103°. The I–O distances are shorter than usual (1.60, 1.65 Å.) and the iodoxy-groups of neighbouring molecules approach one another very closely. The chlorine atom is displaced from the plane of the benzene ring, and the I–C bond does not make equal angles with the adjacent sides of the ring.

¹⁷⁴ Klug, *Acta Cryst.*, 1950, **3**, 165. ¹⁷⁵ Robertson, *ibid.*, 1948, **1**, 101.

¹⁷⁶ Watanabé, Saito, and Chihara, *Sci. Papers Osaka Univ.*, 1949, No. 1, p. 9.

¹⁷⁷ *Ibid.*, p. 1.

¹⁷⁸ Klug, *Nature*, 1947, **160**, 570.

¹⁷⁹ Archer, *Acta Cryst.*, 1948, **1**, 64.

(c) *Nitrogen compounds.* The crystal structure of *p*-dinitrobenzene cannot yet be considered to be entirely satisfactorily elucidated. The early work, based on Fourier projections, led James, King, and Horrocks to the conclusion that the molecule was centrosymmetrical but distorted so that the benzene ring was not regular, the nitro-groups not coplanar with it, and the N–O distances unequal. Criticism of these distortions by Pauling led to a repetition of the analysis by Llewellyn¹⁸⁰ utilising three-dimensional methods for greater accuracy. He obtained a set of atomic co-ordinates which gave a disagreement factor of 0·24, and he stated that they corresponded to a planar molecule, a regular benzene ring and equal N–O distances, whereas in fact they require angles of $11\frac{1}{2}^\circ$ between the planes of the NO_2 groups and the benzene ring. An independent investigation by Abrahams¹⁸¹ seems to indicate that there is a small angle between these planes, but it is clear that more careful three-dimensional analysis is required if the finer details of the structure are to be elucidated. As reported in 1946, the structure of *m*-dinitrobenzene was reconsidered by Archer¹⁸² and the reputed space-group shown to be incorrect. A new trial structure was proposed and the principal Fourier projection of the unit cell calculated; this showed the molecule almost completely resolved, but gave no reliable evidence of any small deviations of the nitro-groups from the plane of the benzene ring; this has been independently confirmed by Gregory and Lassettre.¹⁸³ The bond lengths quoted in these two accounts are not identical but, since the structure is one in which there is adequate resolution in only one projection, it is unjustifiable to attach any quantitative significance to the deviations found. In *p*-nitroaniline⁶¹ the evidence is in favour of a symmetrical nitro-group coplanar with the benzene ring, the N–O distances being slightly greater than those found in the dinitrobenzenes, while the C–N distances appear to be somewhat short. Considerable interest centres on the remarkably close approach of one oxygen atom to the carbon atoms of the adjoining molecule: distances of 2·66, 2·99, and 3·03 Å. are found, all much shorter than the normal van der Waals value of 3·4 Å. It is suggested that a powerful attraction, possibly of an electrostatic nature, exists between the atoms concerned, a self-complex being formed by the nitro-group of one molecule acting as "acceptor" while the benzene ring of another molecule acts as "donor." Independent evidence of complex formation in *p*-nitroaniline comes from the ultra-violet absorption spectrum and the entropy of vaporisation, and the authors incline to the view that this attraction may be the cause of some molecular complexes formed between aromatic nitro-compounds and polycyclic aromatic hydrocarbons although no evidence of short intermolecular distances has as yet been found. By analogy with the properties of structures involving short hydrogen bonds between molecules, it would be expected that the thermal expansion parallel to the short intermolecular C–O linkage would be anomalous. This has been confirmed by McKeown,

¹⁸⁰ *J.*, 1947, 884.¹⁸² *Proc. Roy. Soc.*, 1947, **A**, 188, 51.¹⁸¹ *Acta Cryst.*, 1950, **3**, 194.¹⁸³ *J. Amer. Chem. Soc.*, 1947, **69**, 102.

Ubbelohde, and Woodward¹⁸⁴ who find for the total contraction from 288° K. to 90° K. the coefficients :

$$\begin{aligned}\alpha_{11} &: 2.95 \times 10^{-2} \quad (\text{at } 55^\circ \text{ to } c \text{ axis, i.e., within } 11^\circ \text{ of direction of short} \\ &\quad \text{" bond "}), \\ \alpha_{22} &: 0.24 \times 10^{-2} \quad (\text{parallel to } b) \\ \alpha_{33} &: 0.45 \times 10^{-2}\end{aligned}$$

The molecular complexes of 4 : 4'-dinitrodiphenyl with diphenyl, 4-bromo- and 4-iodo-diphenyl, benzidine, etc., have been shown to be all of the same type as that previously described with 4-hydroxydiphenyl, the proportions of the two components being determined by geometric factors. The complexes with 4-bromo- and 4-iodo-diphenyl show diffuse X-ray scattering explained in terms of random displacements of the latter component along the holes in the lattice of dinitrodiphenyl molecules. No close intermolecular approaches appear to occur in these complexes.^{185, 186, 187}

The mode of dimerisation of nitrosobenzene has previously been uncertain, but two independent investigations (of dimeric *p*-bromonitrosobenzene¹⁸⁸ and dimeric tribromonitrosobenzene¹⁸⁹) have shown conclusively that the molecular formula is (VI) and not e.g. (VII), the positions of the formal



charges not being definitely known owing to the approximate nature of the bond lengths so far determined. In the *p*-bromo-compound the molecule is centrosymmetrical, the planes of the benzene rings being parallel but staggered (cf. dibenzyl), whereas the tribromo-molecule has a two-fold axis of symmetry, the benzene rings being twisted in opposite directions by about 72° from the plane of the nitroso-groups. The difference is probably due to the effect of the extra bromine atoms which have to be packed in.

Aniline hydrochloride and hydrobromide form ionic structures of differing types. In the former,⁵² all the cations point in the same direction in the lattice and each nitrogen atom has three contacts with chlorine ions at 3.17 Å.; the chlorine ions are more than 5 Å. apart, and the determining factor in the packing is the size of the cation. In the hydrobromide¹⁹⁰ however there are cations facing in opposite directions, lying on the two-fold axes in the space-group P2₁22₁. Each nitrogen atom makes contact with four bromine ions at about 3.5 Å., and the arrangement is somewhat similar to that in some alkylammonium halide structures.

¹⁸⁴ *Nature*, 1950, **166**, 69. ¹⁸⁵ Saundier, *Proc. Roy. Soc.*, 1947, **A**, **190**, 508.

¹⁸⁶ James and Saundier, *ibid.*, p. 518.

¹⁸⁷ van Niekerk and Saundier, *Acta Cryst.*, 1948, **1**, 44.

¹⁸⁸ Darwin and Hodgkin, *Nature*, 1950, **166**, 827.

¹⁸⁹ Fenimore, *J. Amer. Chem. Soc.*, 1950, **72**, 3226.

¹⁹⁰ Nitta, Watanabe, and Taguchi, *X-Rays*, 1948, **5**, No. 1, p. 31.

The polymorphism of *p*-iodo-*N*-picrylaniline has been studied by Grison with some very interesting results.⁵⁷ Three crystalline varieties (red, orange, and yellow) all appear together on recrystallisation of any one. The orange is the stable variety at ordinary temperatures; the red form is stable at temperatures near the melting point; and the yellow form is meta-stable. X-Ray analyses demonstrate that the molecule preserves its stereochemical form almost unchanged in all three forms; only in the red form is there a slight reduction of the valency angle at the amino-nitrogen atom, the molecule becoming a little more compact. This together with other minor differences can be interpreted as the outcome of rotations about the single C-N bonds according to the exigencies of packing; for example, steric interactions appear to be the governing factor in the inclination of the nitro-groups to the plane of the benzene ring. The polymorphism is thus caused by the same molecules being packed in three different stable ways. The energies of the three forms must be nearly equal since they all appear

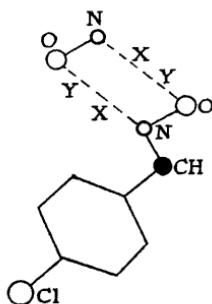


FIG. 10.

syn-p-Chlorobenzaldoxime molecule, with hydrogen bonds (broken).

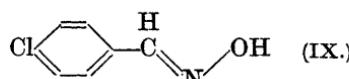
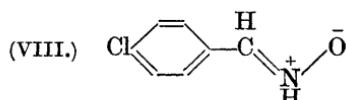
simultaneously from solution. A further form, obtained when a melt is cooled, and described as vitreous, clearly represents the result of molecules being unable to take up one of the stable packing arrangements. The presence of a hydrogen bond between the amino-nitrogen atom and one of the oxygen atoms of an *o*-nitro-group is thought to explain the absence of basic properties in the picrylanilines. Some fairly short intermolecular distances (about 3 Å.) occur in all three structures.

Observations, by Crooks,¹⁹¹ with polarised infra-red radiation led to predictions of the directions of the C_6H_5-N , $N-H$, $C=O$, and $C-CH_3$ bonds in the structure of acetanilide which facilitated the early stages of determination of the atomic co-ordinates. A short note by Brown and Corbridge¹⁹² gives the arrangement of the molecules in the unit cell, linked in chains by $N-H-O$ bonds, but does not claim sufficient accuracy to warrant discussion of the bond lengths.

The structure of *syn-p*-chlorobenzaldoxime confirms the configuration with the hydrogen atom attached to carbon and the oxygen atom attached to nitrogen on the same side of the C-N double bond.¹⁹³ As shown in Fig. 10,

¹⁹¹ *Nature*, 1947, **160**, 17. ¹⁹² *Ibid.*, 1948, **162**, 72. ¹⁹³ Jerslev, *ibid.*, 1950, **166**, 741.

the nitrogen and the oxygen atoms of adjacent molecules are engaged in hydrogen bond formation in a manner which makes it possible that the hydrogen atoms are at XX or YY. If it is accepted that the rules of stereochemistry apply with smaller force to the atom on the side of the hydrogen bond remote from the hydrogen atom (Pauling),¹⁹⁴ then the hydrogen atoms would be placed at XX, and thus the molecular formula would be (VIII). While this is of interest in connection with *N*-ether formation by oximes, it



is in conflict with generally accepted views that, if tautomerism occurs, the equilibrium is strongly on the side of (IX). A detailed investigation of the crystal structure might settle this question in the way that the lactam-lactim controversy in isatin was settled (see below).

(d) *Salts and esters ; ethers.* Zinc and magnesium benzenesulphonates are isomorphous, crystallising with six water molecules per $X(C_6H_5\cdot SO_3)_2$.¹⁹⁵ Both structures may be described as consisting of sheets of metal atoms surrounded by regular octahedra of water molecules and separated by sheets of benzene rings; the oxygen atoms of the sulphonate groups are hydrogen-bonded to the water molecules at distances ranging from 2.72 to 2.86 Å. The S-C and S-O distances appear to be normal, the valency angle of the sulphur atom being tetrahedral. The isomorphous zinc and magnesium toluenesulphonates have closely similar structures,¹⁹⁶ the *a* axis of the unit cell being lengthened to accommodate the extra methyl groups.

In potassium hydrogen bisphenylacetate¹⁹⁷ there are again planes of metal atoms separated by the aromatic rings, but in this case the oxygen atoms of the carboxyl groups make up the octahedral co-ordination about the metal atoms. The potassium and hydrogen atoms must occupy special positions in the unit cell, and it is found that the potassium atoms lie on two-fold axes; the hydrogen atoms must therefore lie at centres of symmetry, halfway between oxygen atoms 2.55 Å. apart. This situation is similar to that reported for trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$).¹⁹⁸

Aromatic esters have not until recently been studied in detail by X-ray or electron-diffraction methods. Although the structure assigned to diethyl terephthalate¹⁹⁹ is not claimed to have the highest accuracy it shows that the molecule is planar except for a tilt of the ethyl groups of about 9°, and that the C-O bond to the ethyl group is unusually long (1.51 ± 0.05 Å.). The structure is built up of layers between which the ethyl groups and ketonic oxygen atoms make contact at about 3.5 Å.

The structure of quinol dimethyl ether provides evidence that the valency angle of oxygen is here about 120°, in general agreement with the

¹⁹⁴ "The Nature of the Chemical Bond," Cornell, 1939.

¹⁹⁵ Broomhead and Nicol, *Acta Cryst.*, 1948, **1**, 88.

¹⁹⁶ Hargreaves, *Nature*, 1946, **158**, 620. ¹⁹⁷ Speakman, *J.*, 1949, 3357.

¹⁹⁸ *Ann. Reports*, 1949, **46**, 82. ¹⁹⁹ Bailey, *Acta Cryst.*, 1949, **2**, 120.

expectation of Sutton and Hampson.²⁰⁰ In the crystal the molecules assume a planar *trans*-configuration, and there is no indication of rotation of the methoxy-groups. Although the molecule is centrosymmetrical in the crystal it cannot be so in solution, where a dipole moment has been observed. The C—O—C angle appears to have the same magnitude in di-*p*-iodophenyl ether.²⁰¹

(e) *Compounds containing unfused benzene rings.* There is considerable interest in the question of the planarity or otherwise of diphenyl derivatives. Diphenyl itself is known to be planar in the crystalline state because the space-group demands a centre of symmetry in the molecule;²⁰² electron-diffraction studies of its vapour²⁰³ however indicate that the two benzene rings must be inclined to each other at an angle of about 45°. Ultra-violet absorption measurements confirm that the molecule is planar in the crystal, and non-planar in the vapour, and also show it to be non-planar in solution, as confirmed by measurement of a dipole moment.²⁰⁴ The steric repulsion between the 2 : 2'-hydrogen atoms tends to make the free molecule take up a non-planar form in opposition to the tendency towards coplanarity due to conjugation; in the crystal lattice the additional effect of intermolecular forces may be sufficient to make the planar configuration the more stable. (In 2 : 2'-dipyridyl²⁰⁵ the effect of steric forces between the hydrogen atoms is eliminated if the nitrogen atoms are *trans* to the 1 : 1'-bond, and in the crystal structure this configuration has in fact been proved, the molecule being again strictly planar. The fact that the ultra-violet absorption spectrum of 2 : 2'-dipyridyl in solution is similar to that reported for diphenyl however seems to indicate non-planarity in the free molecule.) 3 : 3'-Dichlorobenzidine, 3 : 3'-dibromodiphenyl, and 3 : 5 : 3' : 5'-tetrabromodiphenyl deviate from the *cis*-planar form by about the same angle as diphenyl in the vapour state,²⁰⁶ whereas in solid 3 : 3'-dichlorobenzidine the chlorine atoms are *trans* and the molecule is planar, or approximately so.²⁰⁷ In gaseous 2 : 2'-dichloro-, 2 : 2'-dibromo-, and 2 : 2'-di-*ido*-diphenyl the phenyl rings are rotated from the *cis*-planar position so that the angle between them is about 75°.²⁰⁶ A similar configuration is found in crystalline 2 : 2'-dichlorobenzidine (72°)²⁰⁸ and *m*-tolidine dihydrochloride (71°);²⁰⁹ in these structures the bond joining the phenyl rings is equal in length, within experimental error, to a single C—C bond, but the lengths of some of the bonds in the phenyl rings may be abnormally short.

When the two benzene rings are linked not by a single bond but through one or more atoms, the valency angles at the latter influence the molecular configuration. In diphenylmercury the valency angle at the mercury atom is 180°, and the molecule is again planar and centrosymmetrical in the

²⁰⁰ Goodwin, Przybylska, and Robertson, *Acta Cryst.*, 1950, **3**, 279.

²⁰¹ Pleith, *Z. Naturforsch.*, 1947, **2a**, 409.

²⁰² Dhar, *Proc. Nat. Inst. Sci. India*, 1949, **15**, 11.

²⁰³ Bastiensen, *Acta Chem. Scand.*, 1949, **3**, 408.

²⁰⁴ Merkel and Wiegand, *Z. Naturforsch.*, 1948, **3b**, 93.

²⁰⁵ Cagle, *Acta Cryst.*, 1948, **1**, 158. ²⁰⁶ Bastiensen, *Acta Chem. Scand.*, 1950, **4**, 926.

²⁰⁷ Toussaint, *Acta Cryst.*, 1948, **1**, 43.

²⁰⁸ Smare, *ibid.*, p. 150. ²⁰⁹ Fowweather and Hargreaves, *ibid.*, p. 81.

crystal.²¹⁰ The angle between the two phenyl links at the ketonic carbon atom in 4 : 4'-dichlorobenzophenone is 127°, and the molecule now has two-fold symmetry about the C=O bond, the benzene rings being twisted by 30° about the line joining the chlorine atom to the keto-group.²¹¹ A correlation between the approximate bond-lengths, the dipole moment, and the possible resonant structures has been drawn. Di-*p*-bromophenyl sulphide, disulphide, and sulphone also all have molecules possessing an exact two-fold axis of symmetry.²¹² In the sulphide Toussaint claims to have found the S-C bond to have 12% double-bond character, and he deduces that the C-S-C angle is increased from the theoretical value of 90° to 109½° owing to this partial double-bond character; van der Waals repulsion between the *o*-hydrogen atoms prevents the adoption of a planar configuration, the benzene rings each making an angle of 36° with the Br-S-Br plane. In the disulphide the S-C and S-S bonds are thought to be single, and the inclination of the benzene rings at 43° to the Br-S-S-Br plane arises from steric repulsion of the hydrogen atoms, unaffected by resonance in the S-C bonds; the S-S-C angle is 107°, apparently owing to steric repulsion between the 1-carbon atom and the 1'-sulphur atom. The benzene rings are inclined at 90° to the Br-S-Br plane in the sulphone, where the S-C bond is again single. Owing to the increased tilt of the molecule, the C-S-C angle falls to 100° without steric hindrance. The isomorphous dichloride and dibromide of di-*p*-tolyl-selenium²¹³ have molecular structures essentially identical with those previously found for the diphenylselenium dihalides.²¹⁴ The C-Se-C angle (107°) resembles the sulphur valency angle in the sulphide discussed above, while the halogen-Se-halogen angle is 177°, representing a slight deviation from linearity so that the halogen atoms are bent away from the *p*-tolyl groups. The benzene rings are inclined at 40° to the C-Se-C plane. The selenium-halogen bond distances are approximately 0.23 Å. longer than the sum of the accepted single-bond covalent radii.

The tetraphenylmethane molecule has 4 symmetry, and has been studied as a two-parameter problem:²¹⁵ the angle (θ) of rotation of a phenyl group about the bond joining it to the central carbon atom (measured from a plane parallel to *c*), and the angle (ψ) of rotation of the whole molecule about the *c* axis (measured from the *a* plane). The best fit was obtained with $\theta = 55^\circ$, $\psi = 7.5^\circ$. The structure is an open one owing to the awkward shape of the molecules.

The fully-refined structure of dibenzyl was reported last year. The related compounds *meso*- $\alpha\beta$ -divinyldibenzyl-(3 : 4-diphenylhexa-1 : 5-diene) and *meso*- $\alpha\beta$ -diethyldibenzyl-(3 : 4-diphenylhexane) (X; R = CH:CH₂ or C₂H₅) have been shown to exist in the staggered configuration of dibenzyl in which the plane of the central bonds is approximately perpendicular to the

²¹⁰ Kitaigorodski and Grdenic, *Izv. Akad. Nauk. S.S.R.*, 1948, No. 2, 262.

²¹¹ Toussaint, *Bull. Soc. roy. Sci. Liège*, 1948, No. 1, 10.

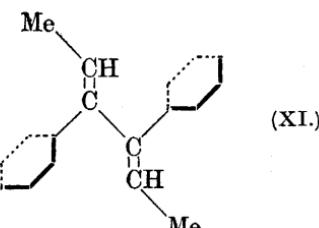
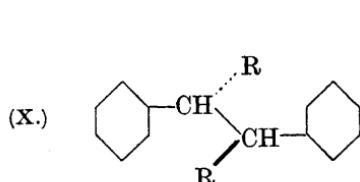
²¹² *Idem*, *Bull. Soc. chim. Belg.*, 1945, **54**, 319.

²¹³ McCullough and Marsh, *Acta Cryst.*, 1950, **3**, 41.

²¹⁴ McCullough and Hamburger, *J. Amer. Chem. Soc.*, 1942, **64**, 508.

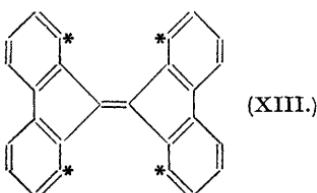
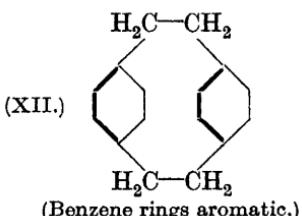
²¹⁵ Sumsion and McLachlan, *Acta Cryst.*, 1950, **3**, 217.

benzene rings.²¹⁶ $\alpha\beta$ -Diethylidenedibenzyl (3 : 4-diphenylhexa-2 : 4-diene) (XI) is concluded to have the *trans-trans*-configuration from considerations



of space-group symmetry and steric interaction. None of these structures has however been analysed in detail.

Two other compounds may be mentioned here, in which the demands of normal bond lengths and valency angles conflict with the van der Waals separation of atoms in the molecule. The first of these is di-*p*-xylylene (XII), a compound so far obtainable only as a result of drastic low-pressure pyrolysis.⁶⁴ The formula shown has been established by X-ray methods, and the bond lengths have normal values, while the valency angle at the CH₂ group is 114½°. If the benzene rings remained planar under these conditions, the distance between them would be 2.83 Å, instead of the usual van der Waals



value of about 3.5 Å. While the substituted carbon atoms of the benzene rings are in fact separated by this short distance, the benzene rings are distorted so that the remaining atoms have a separation of 3.09 Å. The second compound,²¹⁷ bisdiphenylene-ethylene (9 : 9'-difluorenylidene) (XIII), is anomalous from several points of view: it is chemically more reactive and absorbs light of wave-lengths further towards the red end of the spectrum than might be expected by comparison with other members of the homologous series. Steric interaction between the carbon atoms marked * may be expected if the molecule is completely planar since on the basis of customary bond lengths the separation of these carbon atoms will be only 2.5 Å. Unfortunately the crystal structure is rather complex and will not readily yield accurate atomic co-ordinates, but evidence has been deduced that the molecule is in fact centrosymmetrical and approximately planar and that the separation of the carbon atoms marked * is about 2.5 Å.; it is not however possible to say whether there is any tendency to form a doubled radical with opposite charges on adjacent carbon atoms marked *.

²¹⁶ Jeffrey, Koch, and Nyburg, *J.*, 1948, 1118.

²¹⁷ Fenimore, *Acta Cryst.*, 1948, **1**, 295.

(f) *Naphthalene and anthracene derivatives.* A number of naphthalene derivatives have been studied by Kitaigorodski and others, but detailed results are in general not yet available.²¹⁸ The methods of analysis seem not to present any novel features beyond a rather detailed consideration of packing efficiency where the molecules can be approximated in shape by triaxial ellipsoids. Among other structures reported as under consideration, those of α - and β -naphthol are perhaps of greatest interest.²¹⁹ In the former the molecules form close-packed layers with six-fold co-ordination, and the hydroxyl groups are linked in chains by hydrogen bonds (2.54 Å.). The β -naphthol structure is very similar to that of the parent naphthalene, the unit cell being doubled in the *c* direction. The molecules are linked in pairs by hydrogen bonds (2.60 Å.) perpendicular to the *c* axis, and the separation parallel to the *c* axis corresponds to van der Waals interaction. Considerations of packing have been used to solve the structure of the awkwardly shaped di-*n*-octylnaphthalene.²²⁰ Approximate results have also been published for 1 : 5-dinitro-,²²¹ 2 : 6-diphenyl-, and 2 : 6-dicyclohexyl-naphthalene,²¹⁸ all of which have centrosymmetrical molecules; in the 2 : 6-diphenyl compound, the angle between the phenyl ring and the naphthalene plane is 23°. Acenaphthene has been resurveyed, and found to have a flat molecule, the bond joining the CH₂ groups being at least 1.8 Å.,²²² a surprising result requiring confirmation.

The molecule of anthraquinone is also centrosymmetrical, and shows a general similarity to benzoquinone. As in the latter compound, the C=O bond is short (1.15 Å.) while the adjoining C-C bonds are relatively long (1.50 Å.).²²³

cycloOctatetraene. The stereochemistry of this interesting compound is still unsettled: it remains questionable whether it should be classified as aromatic (if it is regular and highly resonant) or aliphatic (if an alternation of double and single bonds exists in the ring). The former view is supported by electron-diffraction study of the vapour: according to the interpretation by Bastiensen and Hassel the crown form with angles 121½° fits the data best, the mean C-C distance being 1.425 Å. with small alternations possible.²²⁴ X-Ray crystallographic evidence (of a somewhat limited nature as yet) leads Kaufman, Fankuchen, and Mark to support the latter view: the tub form with angles 125° and alternate single (1.54 Å.) and double (1.33 Å.) bonds is found.²²⁵ Infra-red absorption measurements also agree with a crown form.²²⁶

Heterocyclic Compounds.—(a) *Six-membered ring fused to five-membered ring.* The most important structural investigation in this group is that

²¹⁸ *Izv. Akad. Nauk. S.S.R.*, 1947, No. 6, 561.

²¹⁹ Kitaigorodski, *Dokl. Akad. Nauk. S.S.R.*, 1945, **50**, 319.

²²⁰ *Idem, Acta Phys. Chem. U.R.S.S.*, 1947, **22**, 309.

²²¹ Sevastyanov, Zhdonov, and Umansky, *J. Phys. Chem. Russia*, 1948, **22**, 1153.

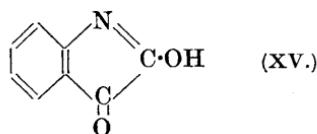
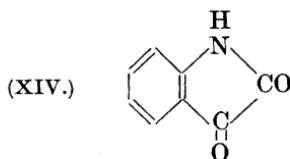
²²² Kitaigorodski, *ibid.*, 1947, **21**, 1085. ²²³ Sen, *Indian J. Physics*, 1948, **22**, 347.

²²⁴ *Acta Chem. Scand.*, 1949, **3**, 209.

²²⁵ *Nature*, 1948, **161**, 165.

²²⁶ Lippincott, Lord, and McDonald, *ibid.*, 1950, **166**, 227.

of isatin²²⁷ which has been carried out with considerable accuracy in order to distinguish between the lactam (XIV) and the lactim (XV) structure.



The best agreement with the observed bond lengths can be obtained by assuming that the lactam and the lactim form contribute in a ratio of about six to one. The molecule therefore exists in a state close to pure lactam. Molecules are related in pairs by a centre of symmetry and linked by N-H-O bonds of length 2.93 Å. which do not lie exactly in the planes of the molecules. Considerable use was made of electron-density maps on the plane $x = 2z$ which show the outline of the whole molecule since the latter makes an angle of not more than 10° with (10̄2); the authors claim that the apparent decrease of the electron-density maxima with increasing distance from the origin is probably due to the greater thermal motion at the benzenoid end of the molecule (a somewhat similar effect was found in geranylamine hydrochloride). In the present case, however, it must be borne in mind that the tilt of the molecule out of the section plane $x = 2z$ means that for atoms remote from the origin the electron density is being sampled on a section of the atom which does not pass through its centre; a decrease of the maxima is therefore only to be expected.

In piazthiole and piaselenole (XVI; X = S or Se) there is again a heterocyclic ring fused to a benzene ring, but owing to the absence of hydrogen bonds the packing arrangement is quite different.²²⁸ The isomorphous structures have been solved in projections by the heavy-atom technique, and a generous estimate of the probable errors in bond lengths has been given. The N-S distances are 1.57 Å., and the N-Se distances 1.85 (± 0.08) Å.

(b) *Two five-membered rings fused together.* The accurate analysis of thiophthen by three-dimensional Fourier methods²²⁹ was mentioned briefly in last year's Reports. This compound was examined in order to discover whether theoretical calculations gave better agreement with the deductions from experimental than that in the case of thiophen (experimental data by electron diffraction). The theoretical calculations for thiophthen are an extension by Evans and de Heer²³⁰ of the molecular-orbital treatment of thiophen by Longuet-Higgins in which it is assumed that the sulphur 3p and 3d atomic orbitals are hybridised and compounded with the carbon 2p orbitals in the formation of molecular π orbitals (*vide* Schomaker and

²²⁷ Goldschmidt and Llewellyn, *Acta Cryst.*, 1950, **3**, 294.

²²⁸ Luzzati, *Compt. rend.*, 1926, 178; 1927, 210.

²²⁹ Cox, Gillot, and Jeffrey, *Acta Cryst.*, 1949, **2**, 356. ²³⁰ *Ibid.*, p. 363.

Pauling²³¹). In the comparison of the bond lengths experimentally determined with those calculated in the above manner it is necessary to establish a relation between bond order and bond length for C-S bonds, in addition to that well established for C-C bonds. The available estimates of the lengths of pure single and double C-S bonds seemed to the authors somewhat unreliable, and they conclude that there is a possibility that the differences between the observed and calculated C-S bond lengths may be due to incorrect standard bond lengths and not to inadequacy in the molecular-orbital calculations. The agreement in the case of the C-C bond lengths was found to be very satisfactory except for the bond common to the two rings which is found experimentally to be 0.05 Å. shorter than the theoretical value. Longuet-Higgins²³² has subsequently pointed out that Evans and de Heer's calculations assume that the σ-bond system is free from strain, whereas the results of the X-ray analysis indicate that the exterior angles at the tertiary carbon atoms are about 135°, and hence the σ-skeleton cannot be strain-free. When the effect of this strain is allowed for, the central bond is shortened by 0.06 Å., bringing the calculated length into excellent agreement with that determined experimentally.

(c) *Pyrimidine and purine derivatives.* The stereochemistry of the amino- and hydroxy-pyrimidines has been established in some detail by Clews and Cochran and Pitt. A reliable basis is thus available from which may be undertaken the investigation of some of the many interesting and important compounds containing these groupings which occur in biological systems. The isomorphous 2-amino-4 : 6-dichloro- and 2-amino-6-chloro-4-methyl-pyrimidines first studied by Clews and Cochran⁵¹ are related to each other in a manner similar to that in *p*-dibromo- and *p*-bromochloro-benzene mentioned above, the methyl groups and chlorine atoms in the second compound occupying at random the 4- and 6-positions which are both occupied by chlorine atoms in the first compound. Weak N-H-N bonds (3.21, 3.37 Å.) link the molecules in sheets, all three nitrogen atoms in the molecule participating; the amino-nitrogen atom forms two such bonds almost coplanar with the molecule, while the nitrogen atoms in the ring each form one non-coplanar hydrogen bond. The chlorine atoms pack together in columns, one having contact with six near neighbours and the other with seven, some of the Cl-Cl distances being unusually short. The C-Cl distances resemble those found in aliphatic compounds more closely than those found in chlorobenzenes, and this is in accordance with the high chemical reactivity. A very careful analysis of 4-amino-2 : 6-dichloropyrimidine shows it to exist in the amino- rather than the dihydroimino-pyrimidine form.²³³ The nitrogen atoms are again engaged in hydrogen-bond formation, and the authors claim that there are low maxima in the electron density near the nitrogen atoms which could be explained as due to (i) hydrogen atoms near the amino-nitrogen atoms, and (ii) unshared electron pairs of the ring-nitrogen atoms, interacting with (i), on the basis of Pauling's theory of

²³¹ *J. Amer. Chem. Soc.*, 1939, **61**, 1779.

²³² *Acta Cryst.*, 1950, **3**, 76. ²³³ Clews and Cochran, *ibid.*, 1949, **2**, 46.

hydrogen-bond formation. The heights of the latter peaks are not much above the background undulation, and the interpretation seems not altogether convincing to the Reporter who, having encountered similar small regions in electron-density measurements of another structure, recently calculated the corresponding " F_c -synthesis" based on the calculated structure factors (without hydrogen-atom contributions) and found that the regions persisted and were thus due to termination-of-series errors. Although this may not be the explanation in the previous case, some such confirmation would carry more weight than the series-termination corrections actually applied.

In 2-hydroxy-4 : 6-dimethylpyrimidine the hydrogen-bond system is complicated by the presence of water of crystallisation.⁶⁰ The structure is made up of interlinked corrugated sheets of molecules united by hydrogen

bonds of three types: (i) from 2-hydroxy- to water molecule (2·8, 2·9 Å.) (not coplanar with the ring); (ii) from 1- or 3-nitrogen to water molecule (2·8, 2·9 Å.) (coplanar with the ring); (iii) from water molecule to water molecule (2·8 Å.). More recent work shows that there is a definite tendency towards a quinonoid type of molecule, with the C=O bond short; this may imply that structures of the type inset make an appreciable contribution to the description of the molecule. If this is so, the negative charge on the 5-position can be correlated with the chemical reactivity at this point.

Adenine hydrochloride has been found by Broomhead²³⁴ to have a planar molecule and bond lengths comparable to those in the aminopyrimidines except for the C-C bond common to the two rings which is long (1·44 Å.). The hydrogen bonding again forms a major factor in determining the arrangement of purine molecules, chlorine ions, and water molecules in the lattice, and it is understood that the hydrogen atoms have all been located in more recent work involving the (F_o - F_c)-synthesis.

The nucleic acids have molecules too large for detailed study by X-ray methods as yet developed, but chemical evidence shows that they are built up from a relatively small number of nucleotides (composed of a pyrimidine or purine with ribose or deoxyribose and a phosphate group), and X-ray methods will no doubt be very valuable in the determination of the steric relations in these compounds of rather unpredictable shape. As a prelude to the examination of one of the nucleotides, cytidilic acid, Furberg has investigated the nucleosides cytidine,²³⁵ and (in outline) uridine, adenosine, and guanosine.²³⁶ Direct confirmation is obtained that cytidine is cytosine-3 β-D-ribofuranoside. The pyrimidine ring has dimensions comparable to those found in the structures mentioned above; the C=O distance is very similar to that in the hydroxypyrimidine, while the C₍₆₎-N distance resembles that in the aminopyrimidines. The C-N bond between the rings is effectively a pure single bond. The D-ribose ring is approximately planar except for one carbon atom which is displaced by 0·5 Å.; the hydroxyl group

²³⁴ *Acta Cryst.*, 1950, **3**, 324., ²³⁵ *Ibid.*, p. 325.

²³⁶ *Acta Chem. Scand.*, 1950, **4**, 751.

attached to this atom then falls in the plane of the ring, as was found by Beevers and Cochran in the case of fructofuranoside. The bond joining the two rings lies in the plane of the pyrimidine ring but makes approximately tetrahedral angles with the adjacent sides of the ribose ring, so that the two rings are nearly perpendicular, contrary to Astbury's prediction. All the active groups are engaged in hydrogen-bond formation and, in addition, the distance from C₍₄₎ of the pyrimidine ring to the O₍₅₎ atom of the ribose ring is short (3.24 Å.) and may represent a weak linkage, possibly to be correlated with the chemical stability.

G. J. P.

Natural Products of Moderate Complexity.—The three compounds we have to consider in this group, strychnine, penicillin, and calciferol, are chemically very different and are linked here by the crystallographic problems involved in the determination of their structures. In all three cases, the X-ray analysis has been achieved largely through the use of heavy atom derivatives to assist in the process of phase determination.

The structure of strychnine has been found independently by two groups, Bokhoven, Schoone, and Bijvoet in Utrecht²³⁷ and Robertson and Beevers in Edinburgh.²³⁸ The analysis in both cases proceeded remarkably smoothly. The Dutch workers used the isomorphous series, strychnine sulphate and selenate, and calculated electron-density projections. From the first of these, a centrosymmetrical projection, they found it possible to select the correct formula and to confirm this by calculation of a second projection. Robertson and Beevers proceeded directly to the determination of the electron density in three dimensions *via* the calculation of a three-dimensional Patterson series for strychnine hydrobromide and the correct selection of the Br-light atom vectors. Curiously enough, although the crystal structures studied differ in symmetry and ionic content, the arrangement of the molecules is very similar in relation to the crystal axes and their appearance in the electron-density contours in the main projections, viewed down 7.58 and 7.64 Å. respectively, is almost identical. The large roughly boat-shaped molecules are fitted together as closely as possible, the spaces between them being filled by the ions and a few odd water molecules. By a happy coincidence, the same structure was deduced on purely chemical grounds almost simultaneously with the first X-ray analysis.²³⁹

The structure analysis of penicillin was also based on the examination of three salts having two types of crystal structure—sodium, potassium, and rubidium benzylpenicillin—and these were investigated, to a large extent independently, by two groups of research workers.⁵³ Here, owing partly to the low atomic weight of sodium and to the special positions occupied by potassium and rubidium in the crystal, the direct phase determination was very incomplete. Extensive trial-and-error analysis by the use of optical diffraction and the direct comparison of rough electron-density patterns obtained in the two investigations played a part in the solution of the

²³⁷ Proc. K. Ned. Akad. Wet., 1947, **50**, 825; 1948, **51**, 990; 1949, **52**, 120.

²³⁸ Nature, 1950, **165**, 690. ²³⁹ Robinson, *ibid.*, 1947, **160**, 18.

structure. At the time that the atomic arrangement shown in Fig. 11 was reached by calculation of the electron density in three dimensions, there was still considerable weight of chemical opinion against the formula found. It is somewhat amusing now, five years later, to find the C–N and K–O distances in penicillin quoted as reasonable standards with which to compare distances found in such molecules as alanine and potassium hydrogen bisphenylacetate. Actually the accuracy of bond-length measurement in the penicillin structure as published is not high, though fully sufficient to establish the general arrangement of bonds within the molecule. A later refinement of the three-dimensional electron-density distribution in potassium benzylpenicillin has provided a series of more accurate bond lengths;²⁴⁰ the greatest deviation of these from generally accepted values is now 0.06 Å. instead of 0.13 Å. in the earlier refinement. The new bond lengths agree very well with those

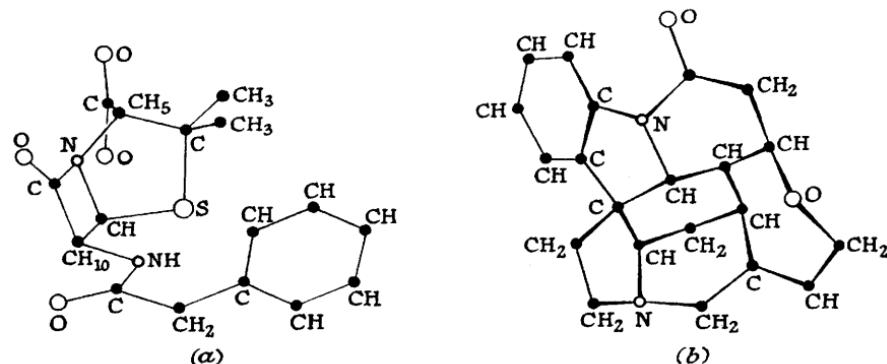


FIG. 11.
(a) *Benzylpenicillin*. (b) *Strychnine*.

to be expected from the straightforward β -lactam formula; within the amide side chain the inter-atomic distances are, for example, similar to those in acetamide within the limits of experimental error.

In the benzylpenicillin molecule, neither the thiazolidine five-membered nor the β -lactam four-membered ring is planar, in agreement with conclusions on other similar rings. The two are fused together in the *cis*-position and the phenylacetamide group is attached to the β -lactam ring on the same side as the thiazolidine-sulphur atom. This arrangement fixes the stereochemical configuration at the two centres $C_{(5)}$ and $C_{(10)}$, as opposite to one another; chemical degradation has established them as D and L respectively. In both crystal structures the molecule has a compact semicircular form, with the thiazolidine and benzene rings not far from parallel to one another. This must largely be due to packing considerations; it enables all the oxygen atoms, both of the β -lactam and the amide groups, as well as the carboxyl groups, to be arranged around the ions to form an ionic layer in the structure, and, as in many inorganic crystals, the change in crystal structure when passing from

²⁴⁰ Pitt, personal communication.

the potassium to the sodium salt enables seven oxygen atoms to make contacts with the potassium ion, while only six make contact with each sodium ion. Owing to the complex geometry of the molecule, however, the packing situation is also very complicated—for example, the oxygen atoms of six different penicillin ions have to make contact with each potassium ion in the potassium salt.

The third crystal structure in this group, that of calciferol 4-iodo-5-nitrobenzoate, is not completely solved. But the single electron-density projection obtained is sufficient to show both the intricate way in which the molecules fit into the crystal and the general form of the molecule itself.²⁴¹ Earlier preliminary crystallographic measurements on calciferol had suggested that the molecule should be not very unlike cholesterol and had thrown some doubt on the chemical evidence for the breaking of ring B.²⁴¹ However, the present more exact data show that, in this crystal, ring B is not only open but wide open. The molecule is fully extended and the projected atomic positions agree very well with those expected from chemical evidence. Certain stereochemical details can be added—for example, the arrangement at the 22 : 23 double bond is clearly *trans*.

The use of heavy atoms in all these structures to achieve at least partial phase determination raises the question of how long the process can be continued—what is the maximum size of molecule for which this process might work. Calciferol 5-iodo-4-nitrobenzoate has 41 atoms* and is the largest organic molecule for which an electron-density projection showing individual atoms has yet been published. But there are a number of other similar-sized molecules under investigation, including chloromycetin and aureomycin,²⁴² and at least one larger, of which the crystal structure has been essentially solved.²⁴³ The possibility of structure analysis, with or without a heavy atom, certainly does not end at this order of complexity. In a rough way this can be shown by the comparison of the average scattering power of a single heavy atom in the crystal unit to that of a number of carbon atoms, assuming as correct the deduction by Wilson²⁴⁴ and others of the statistical distribution of the intensities of X-ray reflections in complex crystals. It seems most probable that, in practice, the limit will be set by the intensities of the observable reflections. As the molecules become more complex, reflections from planes of small spacing no longer appear on X-ray photographs. For a molecule of the order of magnitude of vitamin B₁₂, for example, for which the crystal asymmetric unit has a weight of about 1600, no reflections are visible from planes with spacings smaller than about 1.1 Å.²⁴⁵ At this limit, it should still be possible, at least theoretically, to calculate an electron-density distribution showing resolved atoms. But when we come to molecules of much greater weight, such as proteins, this is

²⁴¹ Bernal, Crowfoot, and Fankuchen, *Phil. Trans.*, 1940, **239**, A, 135.

²⁴² Dunitz and Leonard, *J. Amer. Chem. Soc.*, 1950, **72**, 4276.

²⁴³ Vand, Personal communication. ²⁴⁴ Wilson, *Acta Cryst.*, 1949, **2**, 318.

²⁴⁵ Hodgkin, Porter, and Spiller, *Proc. Roy. Soc.*, 1950, **B**, 136, 609.

* Not counting hydrogen.

no longer true, beautifully crystalline though many proteins may be. The interpretation of their crystal structures raises problems of an altogether different dimension from those discussed here and must be left for yet another Report.

D. C. H.

We were very greatly assisted in covering the field of this Report by the use of the classified bibliography issued by the American Society for *X-Ray and Electron Diffraction* and the American Crystallographic Society, and also of the abstracts prepared for forthcoming Structure Reports through the International Union for Crystallography. We are much indebted for the loan of these to Professor Lonsdale and Dr. A. J. C. Wilson. We also acknowledge the help we received in preparing the report from Dr. Clara Brink and Dr. June Broomhead.

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