THE STRUCTURE OF WATER AND ITS BIOLOGICAL IMPLICATIONS

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The very fact that water is a liquid and not a gas indicates a very strong attachment between the molecules. Compare water, for instance, with hydrogen sulphide, which on account of its greater molecular weight ought to be a more coherent substance. And yet it is a gas. Compared also with the hydrides of the other elements of the first row of the periodic table—methane, ammonia and even hydrofluoric acid—it has greater coherence. The explanation of all this, we now see, is due to the character and the geometry of its bonding. This is by means of the so-called hydrogen bond which exists whenever a relatively unscreened proton is attached to another atom. This gives rise to a polarization which makes a subsidiary bond much weaker than the covalent bond, but stronger than the normal van der Waals force. As we progress from methane to hydrofluoric acid, this hydrogen bond gets progressively stronger. What gives water its peculiar properties is the fact that, whereas in ammonia there are potentially three hydrogen bond donors to one acceptor and in hydrofluoric acid one hydrogen bond donor to three acceptors, the two exactly balance in water. The two positive protons find two negative lone pair electrons in the oxygen to join in with and consequently produce a four-co-ordinated cross-linked structure of exceptional strength and stability.

However, after stating this, I am not going to describe the chemical properties of water in relation to life, all-important as they are. These are other questions altogether, though they obviously also come very much into biology. The physical properties are quite enough to consider, and they depend very largely on the hydrogen atoms and on their attachment both to the rest of the molecule, and to the other molecules. The properties of water also depend on how far the hydrogen is from the oxygen, that is, on the acidity of the medium. At low pH's the hydrogen moves out from the oxygen as far as 1·05 Å, at high pH's it moves to 0·85 Å. In neutral water it is 0·96 Å. A fairly strong oxyacid has the hydrogen right out, leaving it a negative oxyion and transferring the hydrogen to a neighbouring water molecule, thus converting it into a positive hydroxonium ion, OH_3^+. Conversely, an alkaline ion in solution attracts an electron from a neighbouring

water molecule, making it a hydrated positive ion and leaving a corresponding OH^- ion. I will not deal further with these extreme states but concentrate on water at fairly neutral pH's which may, however, hold positive or negative ions or neutral molecules with hydrophilic substituents in solution.

But, before I actually come down to discussing the different states of water, I might deal with the main physical feature of water, namely, that it is a liquid and not a crystal. Now, the fluidity of water seems to us hardly to require any explanation: it is indeed included in our earliest notions of a liquid and that was why, when the Greeks talked about the *element water* they did not really mean water in the modern chemical sense, they meant the *liquid* state, especially its fluidity. It is only recently that we are really getting a clue as to what the liquid state is. Oddly enough, the first serious work on the liquid state was done on water (Bernal & Fowler, 1933), which was a great mistake. It is true it is the commonest liquid, but it is also the most anomalous of liquids; it has anomalies in practically every single one of its physical properties. The tables of physical properties of water prepared for this conference (p. 3), consist mainly of anomalies. The ideal liquid is something quite different. We do know such an ideal liquid: we have it in the laboratory. Mercury as a monatomic metallic liquid is much more like an ideal liquid than water is. Even now, the only liquids for which we have any idea of the detailed structure are the monatomic liquids, of which there are four rare gases in the liquid state and a few molten metals, which apart from mercury cannot be studied very easily.

Recent studies have shown that there are more states of matter than we were accustomed to in elementary physics. We talk about solids, liquids and gases. We can measure their properties and this is good enough to start with. But we have not an equal understanding of their structures. The tricky one is the liquid state. We seem to have quite a good theory of solids now; the whole of crystal structure analysis deals with solids. They consist of three-dimensional arrays of atoms or molecules in regular order. For gases we have long had a kinetic theory, with widely separated molecules dashing around. But liquids, all liquids, are neither one nor the other. They all have arrangements of atoms which are nearly as close together as they are in the solid. Actually, atom for atom they are *as* close or closer together than they are in the solid, and, at the same time, liquids have no regular structure and are in consequence fluid with no shear strength. They completely lack inner regularity, although they are in what we call the condensed state. Now, the structure of liquids has been a study which has occupied me very much in these latter years. Most of my detailed work has been, however, on the structure of ideal liquids, and

what I can say about water in various conditions is essentially by analogy, for at this point I began my studies.

The study of the properties of water in relation to its biological function, however, necessarily involve the more anomalous states of water. It will require many thorough-going studies before anything serious—even more, anything quantitative—can be said about them. There are, moreover, a number of gradations between the crystalline regular state and the liquid state. Those gradations have been the subject of empirical study now for a hundred years or so, but are far from being understood. They are those that are normally studied in colloid science: I should call them generalized or subregular crystals. That is, they have not got a 3-D regularity, but they have a 1-D or 2-D regularity. 1-D regularity you are all familiar with now as linear polymers. 2-D's are rare but they are of decisive importance in biology, because, as I will be pointing out later, the whole of intracellular biology is a matter of membranes and membranes are essentially 2-D crystals showing regularity only in two dimensions.

The implications of the different degrees of regularity are shown fully only in three dimensions. Crystallography is essentially built on the notion of identical particles ranged in regular repeat order. Of course, they further imply symmetry, which is a purely geometrical property. But the existence of this repeat order puts limitations on possible symmetries. For instance, in three dimensions, the only possible rotary symmetries are those which have twofold, threefold, fourfold and sixfold symmetry, twofold symmetry including the plane of reflexion. Text-fig. 1 shows the impossibility of making a 2-D arrangement, for instance, of pentagons. A floor cannot be paved regularly with pentagons but the inside of a sphere can be. This turns out to be either the icosahedron, the pentagonal dodecahedron, or some combination of them, the kind of ornament one sees on roofs of mosques, or, on a small scale, in globular virus structures. When objects are of essentially low symmetry, whether they have intrinsically low symmetry, or whether they get low symmetry by random movement, it is impossible to get regular three-dimensional arrangements; in other words, the substance will not crystallize.

Now, irregular arrangements are much more difficult to construct. You can put it in words very simply: that is, any kind of object at all, bits of chalk, sticks and stones, anything you like, can be thrown about and they come down in a heap. Think of a heap of matches; when they are packed in the box as you get them from the makers, they are in a regular arrangement. Now, while the geometry of regular arrangements has been most thoroughly studied—it comprises the whole subject of crystallography—the geometry of irregular arrangements is only just beginning to be studied. Plate 1,

fig. 1, is a picture of the first model which I made, about 4 or 5 years ago now, of such an arrangement. Each one of the lines is a link between two atoms, black rubber balls simulating the atoms with coloured spokes linking them. But the essential point is, this was made deliberately wrong. The links are coloured differently, each different colour corresponding to a different length. If we try and join spheres together, not with the same length of bonds but different lengths of bonds, we are forced into such an irregular arrangement.

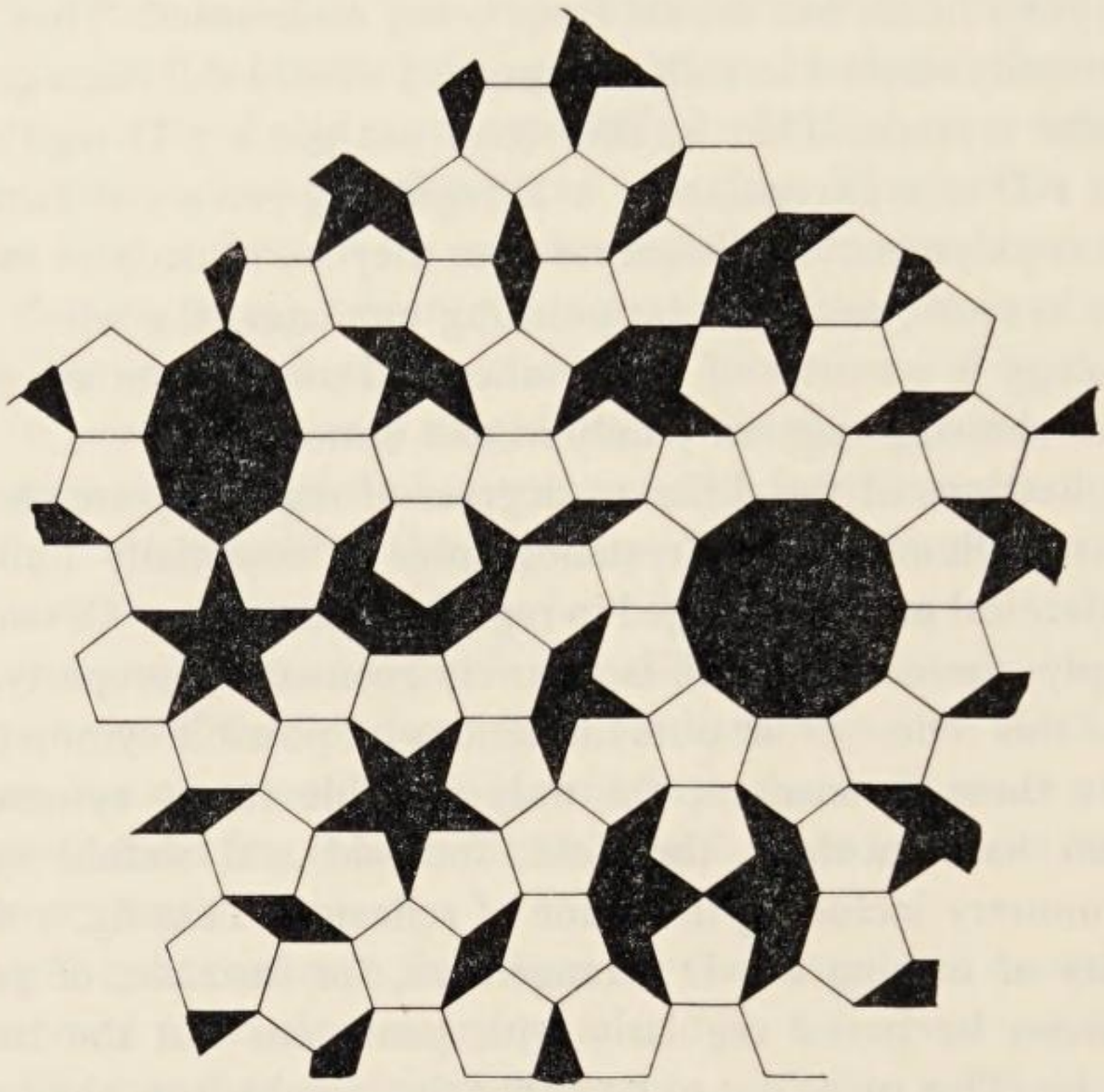

Fig. 1. Fivefold symmetry makes filling space with a regular array impossible.

Now, there was always the possibility that the model I have just shown is biased by the human element. I tried to avoid this by constructing a model entirely by electronic computer, using in the first place only the condition that no two points must be placed too close together. Starting from an arbitrary origin, I picked a point from a random table, or rather the computer picked it. I accepted it only if the distance from the origin was greater than one. Other points were picked in the same way: the distance between them and all the previous points had to be greater than its arbitrary minimum one. If any two points turned out to be too close together, the last one was rejected. It proved a tedious process even for the computer and at the end of the work, when there were about two hundred points, the computer, still working at random, would often have to pick several hundred before one could be found that fitted the condition. But

it did mark an advance, because the fact that it gave the correct distribution function of the distances between the atoms, as measured in real liquids by X-rays, showed we were on the right track.

This model, shown in Plate 3, fig. 1, shows certain other features, but the one that I want to draw your attention to particularly is the one in the middle. There one is looking along a row of atoms, and this is a totally unexpected characteristic of a random structure. Although it is apparently irregular in three dimensions, it has got some limited one-dimensional

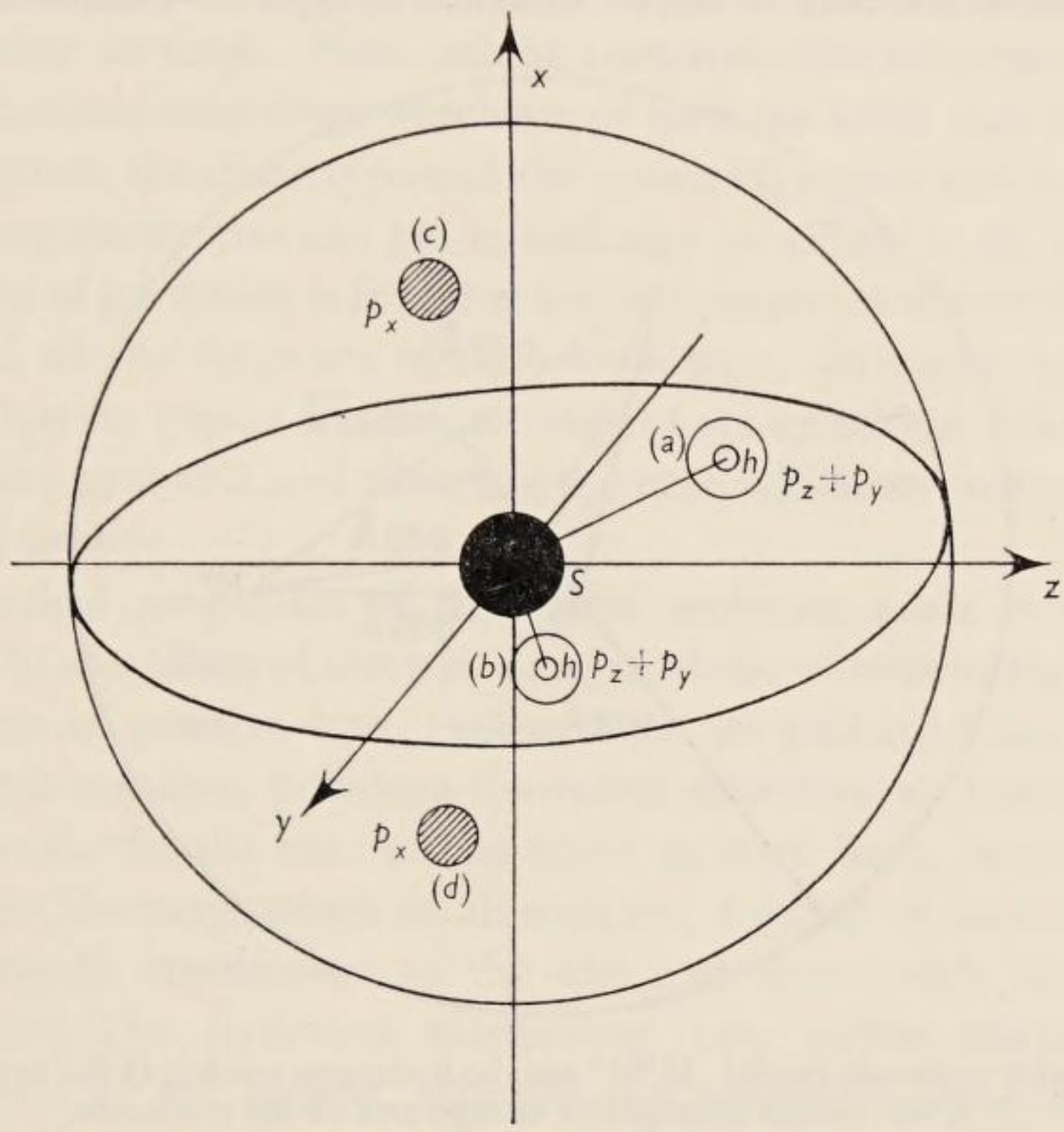

Fig. 2. Electron distribution in the water molecule.

regularity, that is rows of atoms of approximately the same distance apart. They are not quite straight, and around each of the rows there is necessarily a channel. And that is in part the explanation of how liquids flow. The rows can move along their lengths quite easily, but they cannot move across equally easily. The atoms are on little trains, so to speak, with different carriages and running in all directions, up and down and sideways. If a shear stress is applied to such liquid the movements which are in the direction of the relief of the stress will be made more probable than those which increase it, and thus the liquid will flow.

After these discussions of general properties of liquids, I want to return to water. As I have already indicated, the water molecule is unique in that it contains two imperfectly screened hydrogen atoms, and at the other side

of the molecule, in the tetrahedral position, it has two lone-pair electrons, in other words, two positive regions at two corners of a tetrahedron and two negative regions at the other two corners. In Text-fig. 2 is a more detailed picture of the water molecule as I have described it, with its two protons at *a* and *b*, and the other two lone-pair electrons at *c* and *d*. If you look at that in one plane (Text-fig. 3) the centre of the oxygen is at a distance 0·96 Å from one of the hydrogens, and the centre O′ is what you might call the electrical centre of the molecules. This gives the diameter of the molecule in plain water at a centre to centre distance of 2·76 Å. That also gives it its

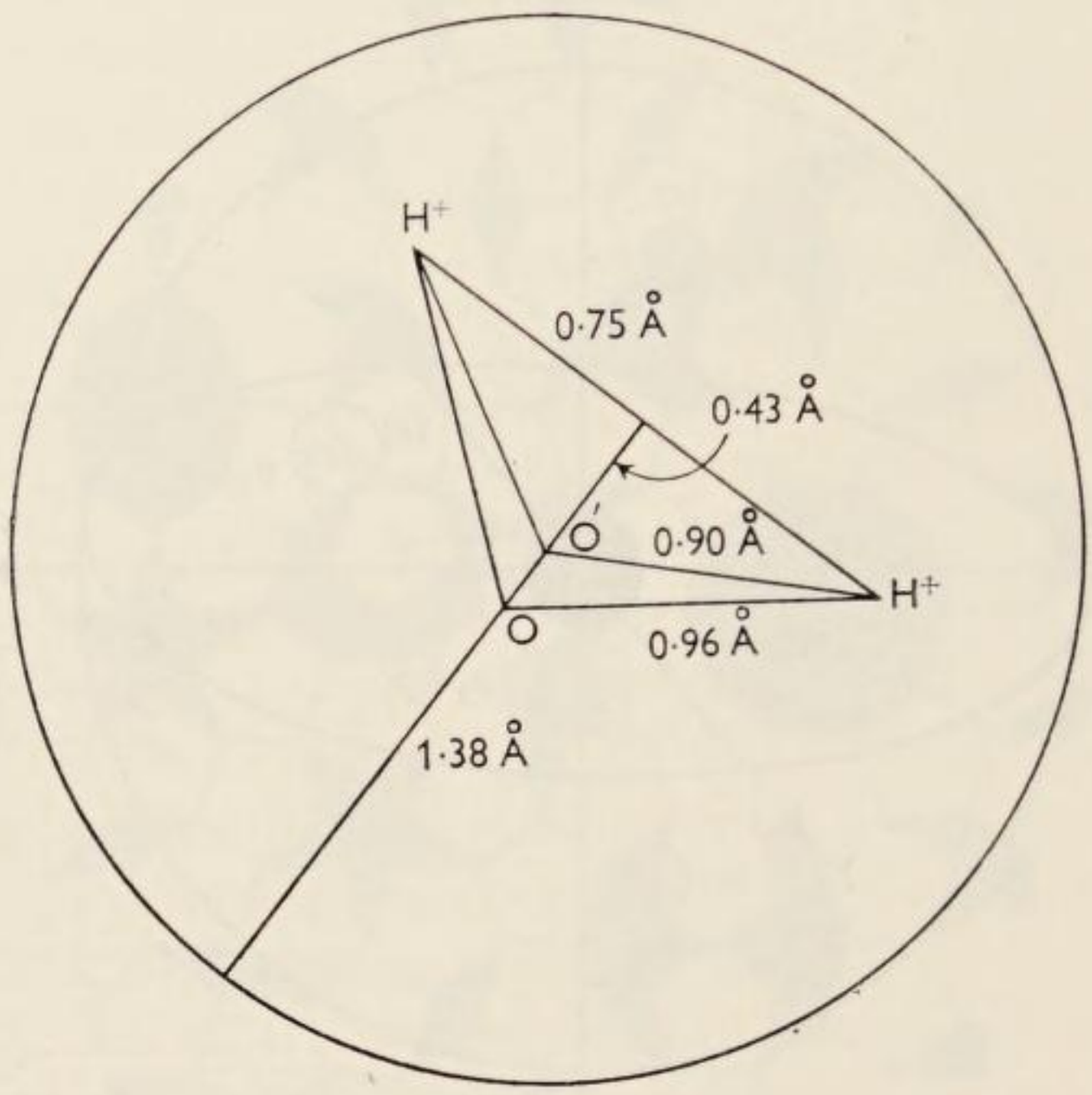

Fig. 3. The water molecule model. H^+H^+ are the hydrogen nuclei; O the oxygen nucleus, O′ is the centre of negative charge and of the molecule.

electrical polarity of μ (dipole moment) = $1{\cdot}84 \times 10^{-18}$ e.s. units. It also means that each one of these water molecules tends to join on to two other water molecules at the positively charged positions and on to two other water molecules at the negatively charged positions by what we call hydrogen bonds. In other words, each molecule tends to have four neighbours. Now this can be done regularly in the varieties of crystalline ice. Plate 1, fig. 2, shows a model based on the form of silica called keatite, the silicon atoms in keatite being considered to be replaced by oxygen atoms (the black balls) and the oxygen atoms in keatite by hydrogen atoms (white beads). This is a beautiful regular arrangement that satisfies all these conditions. It is not water, it is ice, and this is the limit to which you can get in imitating water in regular arrangements.

The best model which I have been able to make of water is the one

shown in Plate 2, fig. 1. In this model of the water structure it has been arranged that each molecule should have four more or less tetrahedrally arranged hydrogen bonds. Further, each oxygen has two hydrogen atoms (white beads) which, so to speak, belong to it. But in the model some of them can have three, and some can have only one, and a change can easily be made from one to the other in the model by redistributing the positions of the hydrogen atoms. In other words, the plain water structure is a structure which satisfies the condition that each molecule has four neighbours, and only four neighbours, and these neighbours necessarily are joined together in rings. Now, in the tridymite-like structure of ice, the rings are six-membered rings which are of both the kinds that the chemists would recognize, the chair type and the crown type, and that is the kind of balanced irregularity you can get in ordinary ice (Plate 2, fig. 2). There is another form of ice which is found at low temperatures where the structure is cubic and all the rings are of the crown type. In water, as the model shows, there is no reason to stick to rings of six members; five-membered rings are more probable and those are the ones which we find in the model structure of keatite.

The electrical properties of the water molecule make it particularly susceptible to the effect of electric charges, those of ions in the first place. The presence of positive ions, except the large positive ions, potassium, rubidium and caesium, polarizes the water structure in their immediate neighbourhood. In the case of the small positive ions, especially highly charged ones like magnesium or aluminium, a group of four or six water molecules attach themselves to the ion and move with it, forming a hydrated ion. The hydrated magnesium ion, radius about 3·3 Å, is effectively one of the largest, whereas the potassium ion, radius about 1·3 Å, which is not hydrated permanently, is one of the smallest. Hydration also occurs around negative ions and not only with the oxygen-covered negative ions of the oxyacids as already indicated, but the hydrogen of the acid exchanges with water leading to the formation of the oxonium ion.

The small ions, monatomic or polyatomic as in the oxyacid ions, in general, produce disturbances of the water structure which are strictly local. While they affect the general physical properties of the solution, they do not alter its essential nature. Much greater changes, however, are produced in water by the presence of large ions or colloidal amphoteric particles.

Thus, besides the normal form of pure liquid water, we have a great many alternative forms that are important in biology. The fact is that a water molecule is so electrically reactive that its arrangement depends on the neighbouring charges. It is polarized by ions so that it forms skins of

molecules around them; if they are negative ions the hydrogens go to them; if they are positive, the hydrogens stick out. The water molecules are also oriented by all surfaces, including the simplest surface of all, which is nothing. In an isolated drop of water the hydrogens are oriented from the surface inwards. Those at the free air–water surface are oriented so that no hydrogen bonds stick up; they all stick in. This is shown by the anomaly in the surface tension of the water, which is twice as great as demanded by Trouton's Rule. It is one of the biggest anomalies in surface tension there is. On hydrophilic surfaces there may be very strong attachments. In other words, the effect of surfaces on water is to polarize its structure to different degrees. The greatest effect is found close to the surface. Here, if the surface is regular as in a crystal, the attached water may be arranged also in crystalline fashion in some form of ice, not necessarily the ice which is formed in pure water. For instance, in contact with the crystals of a clay, such as a montmorillonite, the water causes swelling by pushing the crystalline particles further apart in the perfectly ordinary way. Every time the clay swells by about 4 Å another layer of water is arranged on top of it. This goes on right up to about 40 Å in regular steps. In other words, this is not water in the structural sense at all; it is ice: that is, ionically active surfaces are always covered at ordinary temperatures with layers of ice and the number of layers of ice can be measured quite simply by X-rays. This has been known for years and was done by Hendricks in the first place (Hendricks & Teller, 1942). This kind of adsorbing swelling occurs in inorganic crystals of the clay type, but it also occurs on all hydrophilic organic surfaces.

On most protein molecules there is, for instance, a regular formation of ice; in fact, there are two sets of ice associated with protein molecules, internal and external, neither identical with free water ice. Many protein molecules are hollow inside, or partly so. Inside these protein molecules the water molecules are arranged in definite places, held by hydrogen bonds, but not in any extended regular order. When the sizes of the protein molecules are measured by physical methods, such as by centrifugal sedimentation or optically, the value is always bigger than the real value for the dry protein by the amount of water which is held by it in the form of ice. Perutz (1946) showed this in another way by measuring the quantity of salt associated with the hydrated protein and found that it could best be accounted for by assuming that the amount available to the water was less by a layer of water molecules in which no salt could find place. In other words, the ions cannot penetrate the ice which is attached to the protein molecule: it is ion-free ice amounting to about 30% by weight. This goes, I should say, for practically every surface in a cell.

The degree of orientation of water molecules on extended surfaces varies considerably. We may take it, as a general rule, that the water near the surface up to a distance of 10–20 Å will be bound in this form of ice. Beyond that, up to 100 Å or so, the water will not be so tightly bound and will be able to contain ions, though with restricted possibilities of movement. This is about the limit to which the structure of the water itself is liable to be affected by hydrophilic surfaces.

Beyond that there is an influence exerted through water for quite great distances; by great distances in this case I mean thousands of Ångström units —it has been measured up to 4000 Å but it probably goes further. And this is the basis of the colloid phenomena. These are the so-called long-range forces that make certain arrangements gels and others sols. It is these forces that cause some colloid solutions to separate into two phases, the so-called coacervate phenomenon. I came across this first of all in the solutions of tobacco mosaic virus. These divide spontaneously into two layers, one, the 'bottom' layer, containing about 4% and the other, the 'top' layer, containing perhaps only 0·1% of virus material. The virus is found in both layers but an equilibrium is formed between them which is very susceptible to such factors as pH or ionic concentration (Bernal & Fankuchen, 1941).

Therefore, we have to consider that this is entirely due to the virus particles themselves: the virus particles are slightly acid—effectively they get their charge from the nucleic acid—and they have definite interactions to each other; in other words, they keep in fixed stations, with the big virus particles up to about 4000 Å apart. If the particles are round, then you get division into two liquids, that is, two isotropic phases. If the particles are long, one of the phases is not isotropic, the long molecules of the virus being arranged parallel to each other and although they may wobble they are basically parallel and equidistant. These are so-called tactoids. In the case that has been most thoroughly studied, that of tobacco mosaic virus, the particles are rod-shaped, but the same effect is found to extend to an even greater range with flat particles whether they be clays or, what is more common in biological systems, lipoid membranes. Monomolecular or bi-molecular sheets are formed spontaneously by the two-dimensional, hexagonal close-packing of long-chain hydrocarbons and these will generally react with water, for they contain at one end a water-reacting substituent, whether a carboxy- or phosphoric acid or an amine. The nature of these lipoid membranes has been studied in the industrially important field of soaps and detergents by a number of workers, notably by Astbury and Luzzati.

Plate 3, fig. 2, shows the appearance of a crystal of sodium dodecyl

sulphate in water under crossed nicols. The crystal is seen surrounded by a luminous fringe which is composed of liquid crystals formed from layers of the sulphate, making, with the water, so-called myelinic figures which are shown in unpolarized light in Plate 4, fig. 1. Such figures were first

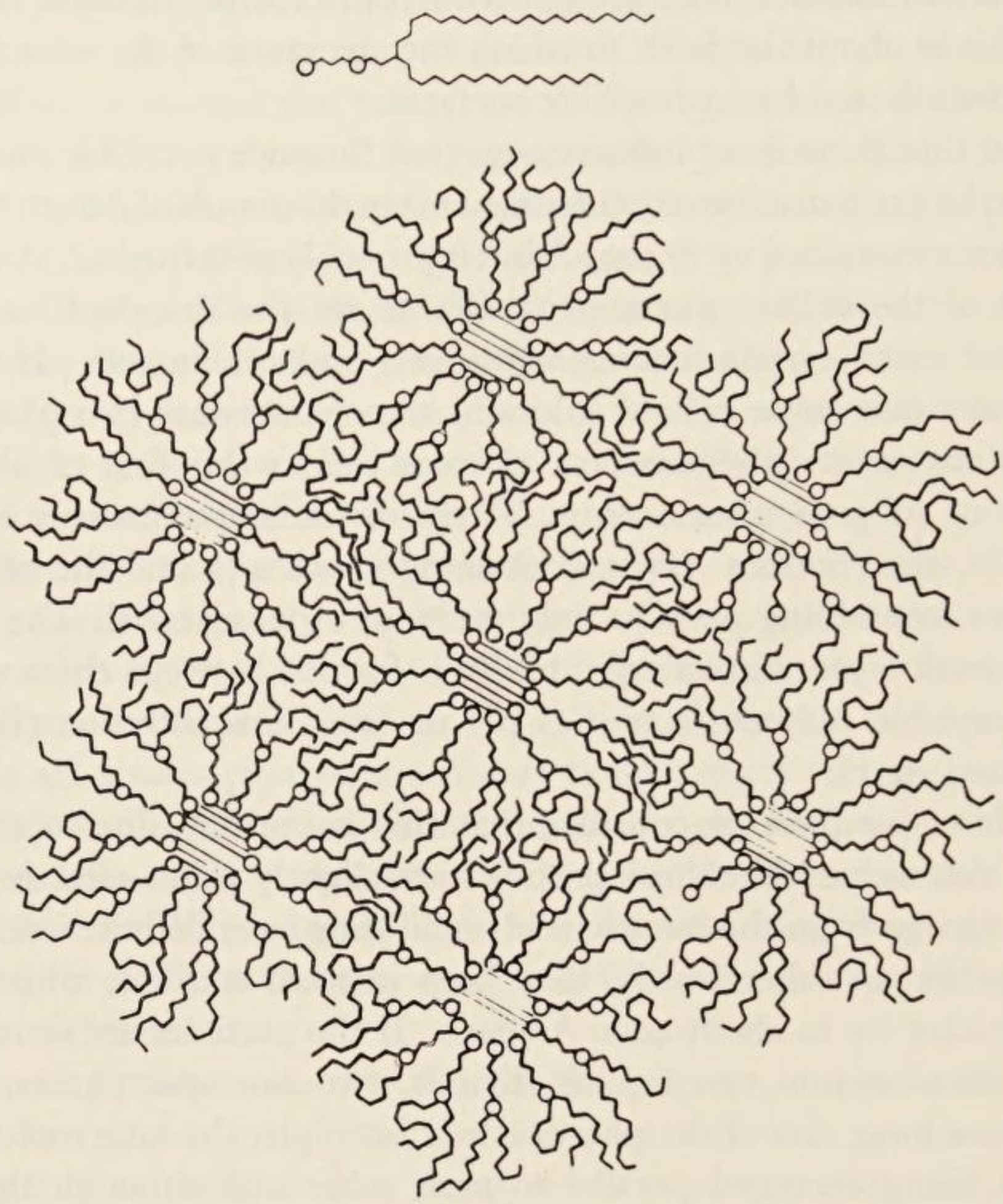

Fig. 4. Arrangement of liquid crystals when amount of water is small.

noticed in biological preparations of nerve and brain. They consist of layers of the substance lecithin or cephalin, wound in regular order, usually round a nerve fibre. Although this multiple-layer structure will occur automatically in artificial preparations, in life it is produced by the movement of a single cell, a Schwann cell, which is associated with the nerve fibre. The detailed structure of such liquid crystals in soaps has been studied by Luzzati (Luzzati & Husson, 1962). Text-fig. 4 shows the arrangement of a liquid crystal when the amount of water is small. Here the hydrophobic ends of the molecule form around themselves a layer of lipoid material and the whole is then organized into a liquid crystal in which the lipoid is the continuous phase surrounding cylinders of water

molecules. In Text-fig. 5 the arrangement is shown reversed in the presence of more water. In this case the lipoid cells are liquid cylinders covered with hydrophilic groups and immersed in water forming a liquid crystal in which water is the continuous phase.

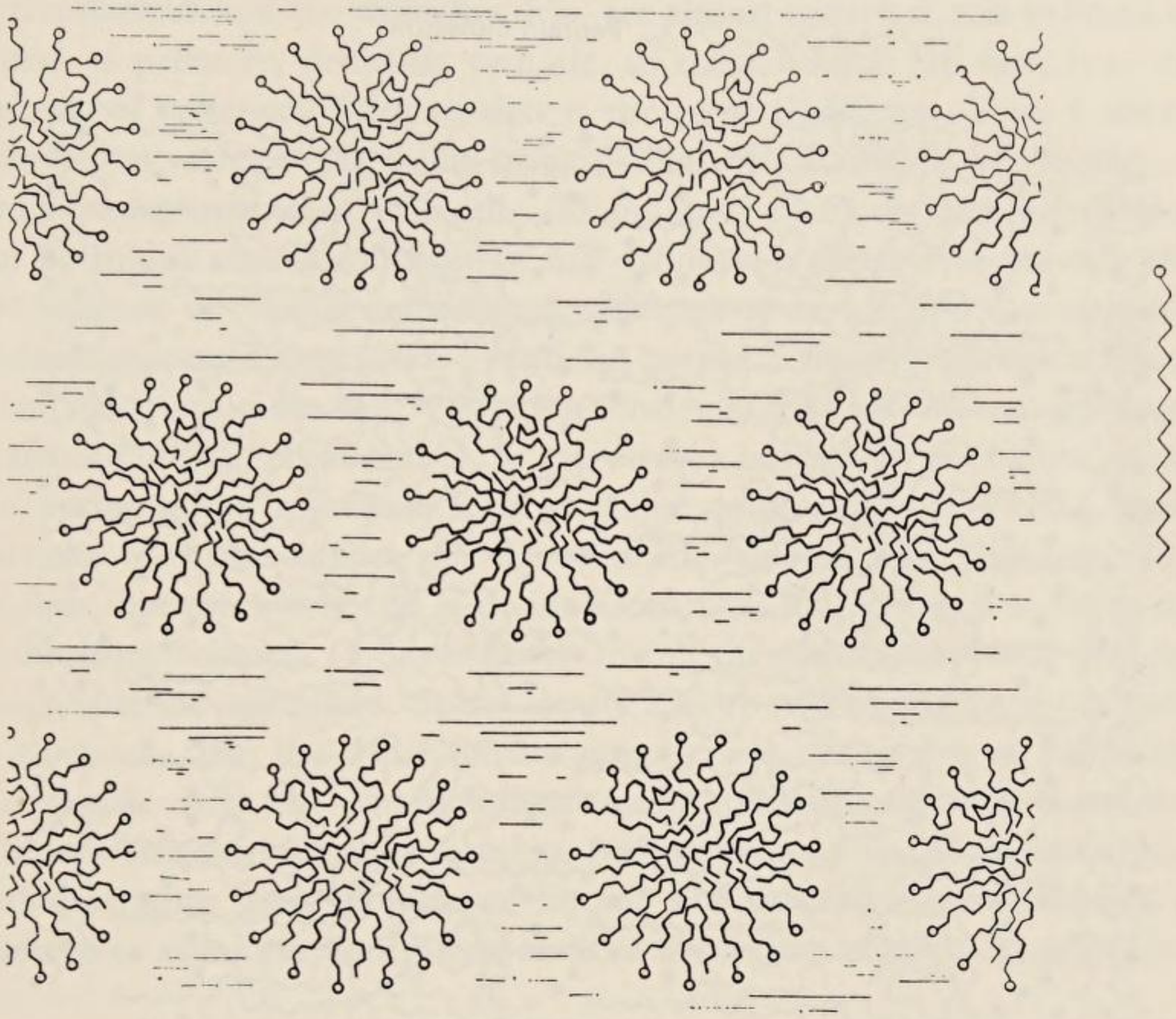

Fig. 5. Arrangement of liquid crystal with greater amount of water.

The type of double sheet membrane which is the commonest in biological systems is shown in Text-fig. 6. Here it appears as a kind of sandwich with lipoid material alternating with protein and the whole immersed in a watery medium. The appearance of such a membrane as shown in the electron microscope is given in Plate 4, fig. 2.

I have now discussed the purely physical and chemical elements that go to make up the kind of structures that are found in living cells. In the last part of this contribution I will try to show some examples of how these are arranged in the cells and what implications can be drawn, from their appearance, of the role of water.

BIOLOGICAL IMPLICATIONS

Water in biological systems exists in three functional forms. The first of these might be called transport water, such as occurs in blood, lymph or sap in the higher organisms. The water that is found here, apart from the

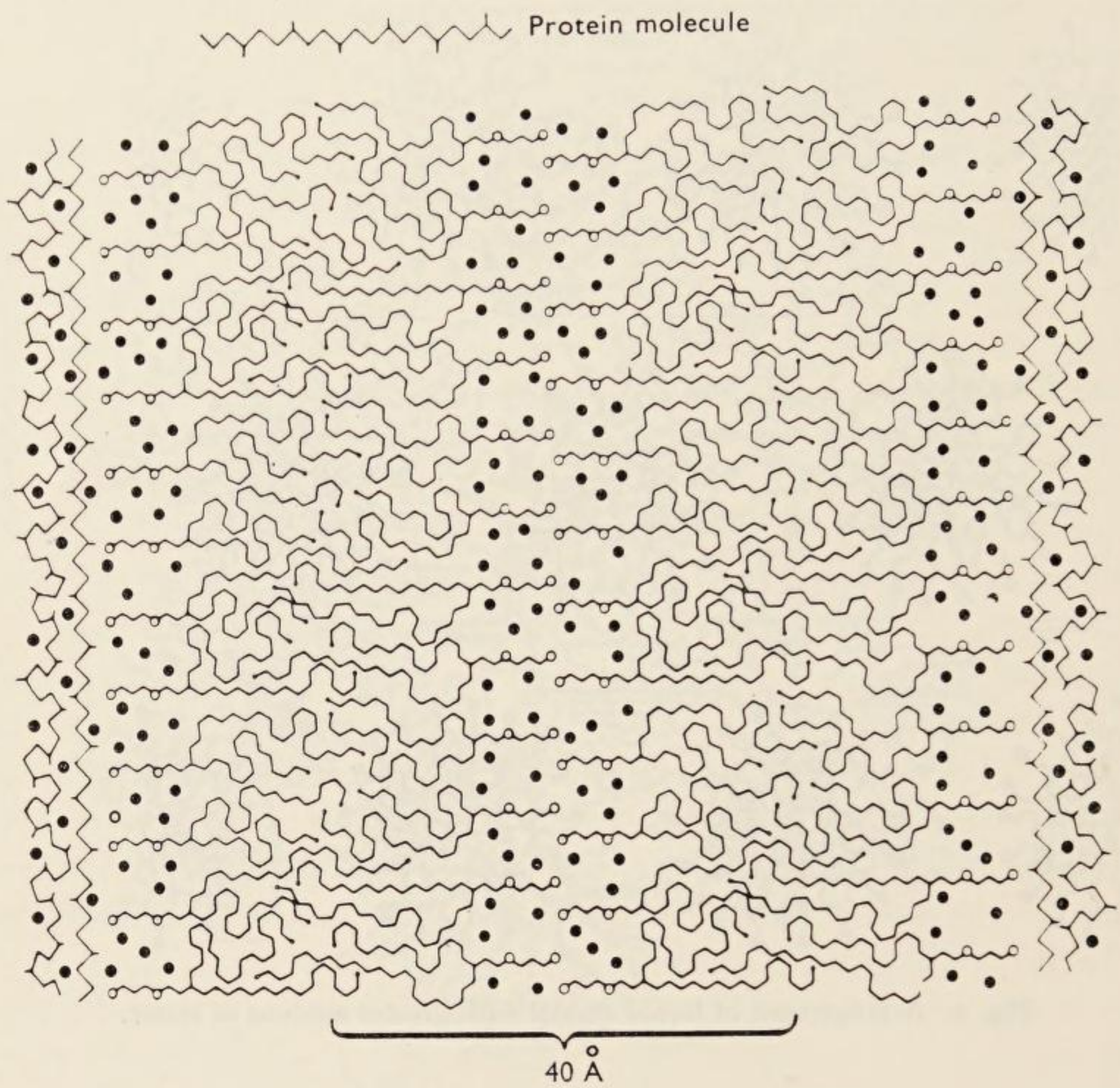

Fig. 6. Double sheet cell with lipoid material alternating with protein.

chemical products that are in solution, is essentially the same as hydrostatic water or hydrodynamic water in a water supply system. It passes through the vessels according to differences of pressure and viscosity. The kind of forces which I have been discussing would not strictly apply to it except in the smallest vessels of all. Besides this we have to consider the water inside the cells and this, as recent research, particularly with the electron microscope, has shown, is divided fairly clearly into two kinds, with different degrees of attachment to the entire cellular structures and particles. The remaining illustrations, which will be fairly familiar to you, illustrate something of this and bring out some of the characteristics of water that I have already described.

We may take the cell as a complex system of membranes whose shape gives definite indications of the state of the water surrounding them. Plate 5 is a picture of a section of a liver cell at comparatively low magnification of 30,000. The membranes in this cell seem to surround a number of separate parts or organelles of the cell. Some, like the external membrane of the nucleus and the mitochondria, are almost spherical and indicate an excess of pressure, probably osmotic, in these bodies. In fact, it is the absence of spherical particles that is the most significant. Plate 6 shows pinocytosis vesicles—flask-like invaginations of the plasma membranes of two adjacent smooth-muscle cells. Membranes which do not show tension can be folded almost indefinitely and delineate a division of the cell into two volumes in osmotic equilibrium with each other, as, for instance, in the endoplasmic reticulum (Plate 7) and the cristae of the mitochondria. These membranes are quite clearly asymmetrical; i.e. the two sides of the membrane are of a different nature, as can be seen in Plate 8, where one side of the endoplasmic reticulum, the so-called rough side, bears the small particles of the ribosomes and the other, the smooth side, does not. This implies that the whole cell is divided into two, in general, not intercommunicating volumes. I have chosen to call the water in contact with the rough side the *endoplasm*. It has clearly a more viscous nature, more body so-to-speak, than the water on the smooth side, which I have called the *endolymph*. It is the endolymph that can communicate with the extracellular water even when the membrane is continuous, by a process of forming and separating small globules of liquid. The process is reversible and is referred to as micro-pinocytosis, and the water may be taken in, or pushed out.

The main point I want to make is in relation to the forces which I was describing between hydrophilic membranes so that no part of the cell except that in the interior vesicles is at a distance of more than a few hundred Ångström units from some other part of the membrane and consequently a force will be always acting between them. From this point of view the multiple folding is no longer accidental but produced by an interaction of adjoining membranes. In the simplest case this can be seen in the shape of the red blood corpuscles, whose bi-concave form is an example of mutual attraction of membranes on different sides.

Biologically speaking there is a case for another explanation. The appearance of cells of practically all organisms, from bacteria to those of the higher plants and animals, seems to show, by the multiple folding of their membranes, that they are derived from ancestors which were much smaller, preserving the same ratio of surface to volume by having spherical inner membranes, the complications, in the strict sense, of the membranes

in higher cells being of the same nature as the loops of the intestine or the convolutions of the brain in organs of a different order of magnitude. As far as I know, the only organisms which show this simplified form are the mycoplasmas, of which the type is that of bovine pleuropneumonia studied by H. J. Morowitz (Morowitz & Tourtellotte, 1962; Whitelock, 1959). This is, although a parasitic organism, capable of independent life in a non-cellular environment. Its diameter is only of the order of 500 Å, no bigger than the higher viruses, and all its inner parts, corresponding to the organelles of higher cells, seem to be spherical.

That is as far as I can go and, as this is an introduction from the physics side, I hope that details will be filled in by the subsequent contributions. I will finish by emphasizing one point—that until we know very much more of the micro-structures, much more than the kind of thing shown in Plates 5–8, we cannot really argue about water in cells. The protein molecules themselves and, more so, the nucleic acid molecules, which are electrically charged, have such a profound influence on the water all round that this must be understood before any general physicochemical, thermodynamic or otherwise, arguments are used about the cell.

SUMMARY

The structure of water is now fairly generally understood on the simple molecular level. It consists of an aggregate, presumably intrinsically irregular, of water molecules held together by hydrogen bonds. These form a loose-packed aggregate with fourfold co-ordination containing potential holes, nearly as large as those contained in ice. This basic structure, however, is not much in evidence in biological structures for it is easily modified by the presence of neutral molecules, ions and macromolecule surfaces. These can best be considered as affecting water structures on different scales of interactions.

First, interactions of the order of 10 Å or less in which the water molecules are closely bonded to something like an ice structure. Thus, as Perutz has shown, a water molecule in the immediate neighbourhood of protein molecules is bound to the protein and travels with it.

Secondly, in the intermediate layer ranging from 10 to 100 Å, the structure of water is dominated by the neighbouring molecular surfaces. In this state of water there is, however, no limitation to the movement of small molecules and ions in solution.

Finally, there is a structural effect which stretches out much further, to distances of the order of 4000 Å. Here there is no question of the structure being different from that of free water; apart from the presence of soluble

molecules it is of essentially electrostatic character—so-called long-range forces between all macromolecules or between isolated macromolecules and bonded surfaces.

All these three aspects of water structure have important biological bearings. The first implies that all micromolecules and the surfaces of macromolecules have attached water molecules in a rigid state, diminishing by that amount the free water available for biological processes. The intermediate range applies to the many double or multiple layers found in cell systems, particularly to the lipid layers which seem to be essential for such varied processes as photosynthesis and optical reception. Finally, the third kind of range of force, the long-range forces, still dominates the arrangement of organelles or other organelle-like parts in cells.

There seems to be evidence for a closely folded membrane system or systems which divide the cell into two different regions of water-containing substances. The first one I have called the endoplasm proper, being in a partly gel-like state, and the second, containing only small molecules, being like more normal water, I have called the endolymph. The whole system is very much folded to secure the maximum ratio of surface to volume. This naturally results in the action of these long-range forces between the different organelles, membranes and particles in the cell, none of which get far enough away for any of it to be treated as a simple water system, except in cells which are swollen with water or contain vacuoles. Endoplasm is continuous with the nucleus and the endolymph communicates with the external environment, which in multicellular organisms may be lymph or blood plasma, by means of a mechanism of pinocytosis. The complicated system of vesicles, organelles such as mitochondria, Golgi bodies, and lysosomes must depend for their precise shape very much on these forces.

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EXPLANATION OF PLATES

PLATE 1

Fig. 1. Model of liquid with balls joined with pokes of different lengths. Each different colour corresponds to a different length.

Fig. 2. Model of keatite-like ice.

PLATE 2

Fig. 1. Model of water structure.

Fig. 2. Model of hexagonal (normal) ice.

PLATE 3

Fig. 1. Model derived from computer synthesis.

Fig. 2. Crystal of sodium dodecyl sulphate in water under crossed nicols.

PLATE 4

Fig. 1. Myelinic figures shown in unpolarized light.

Fig. 2. Double sheet cell membrane as seen in electron microscope.

PLATE 5

Part of a liver parenchymal cell. Mitochondria, rough-surfaced endoplasmic reticulum, lysosomes, Golgi cisternae and a centrosome lie between the nucleus at the top and the bile canaliculus at the bottom of the field (× 30,000).

PLATE 6

The field shows pinocytosis vesicles—flask-like invaginations of the plasma membranes of two adjacent smooth-muscle cells (× 57,000)

PLATE 7

Section through an epithelial cell, to show the nucleus, mitochondria, tubules of rough-surfaced endoplasmic reticulum, free ribosomes and tonofilaments. The cell is clearly delineated by the plasma membrane (× 15,000).

PLATE 8

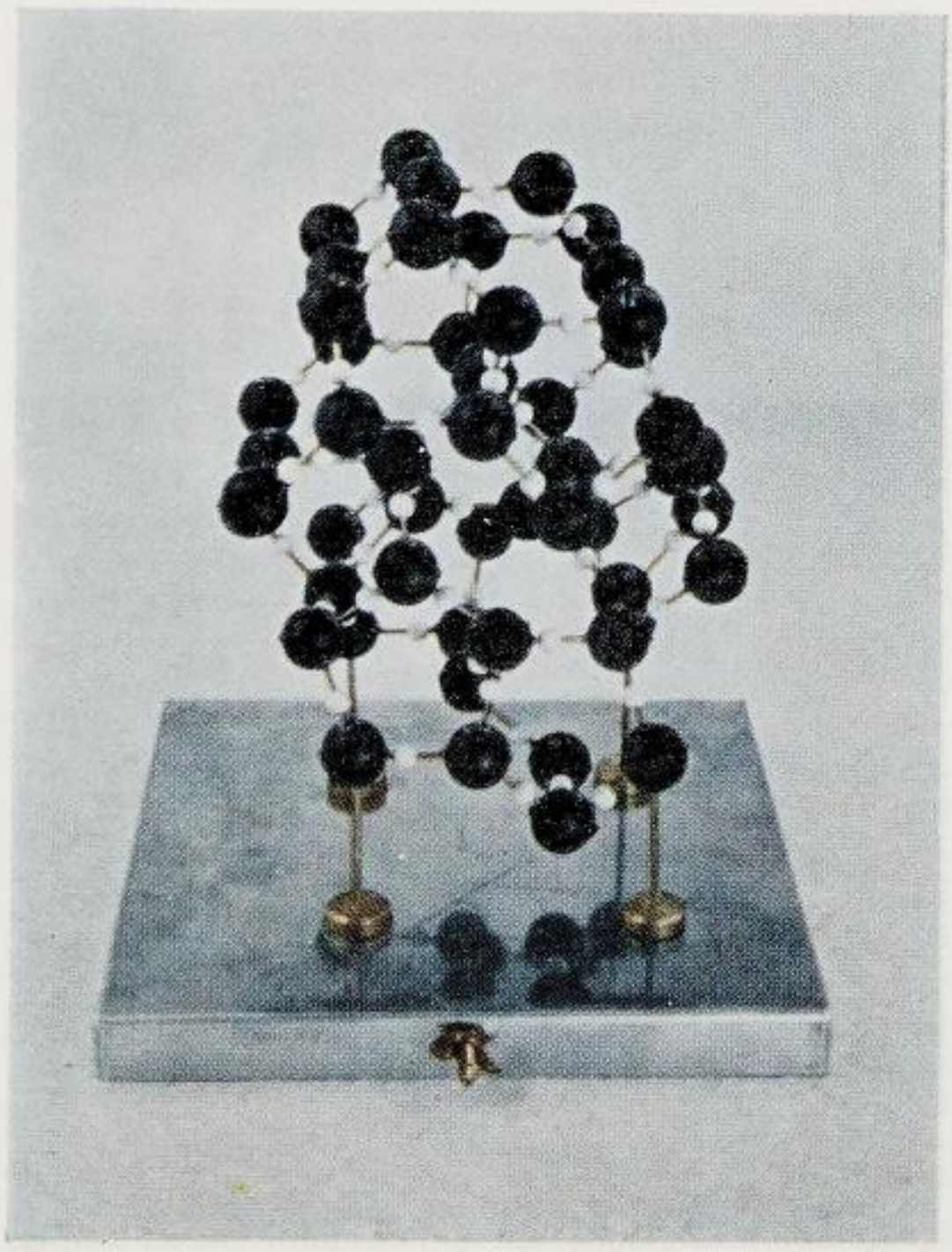
Part of a liver parenchymal cell. Ribosomes can be seen attached to the outer surfaces of the tubules of endoplasmic reticulum. The field also contains a lysosome and mitochondria (× 75,000).

(Plates 5–8 by courtesy of Dr R. Marion Hicks, Bland–Sutton Institute of Pathology, Middlesex Hospital, London.)

PLATE I

1

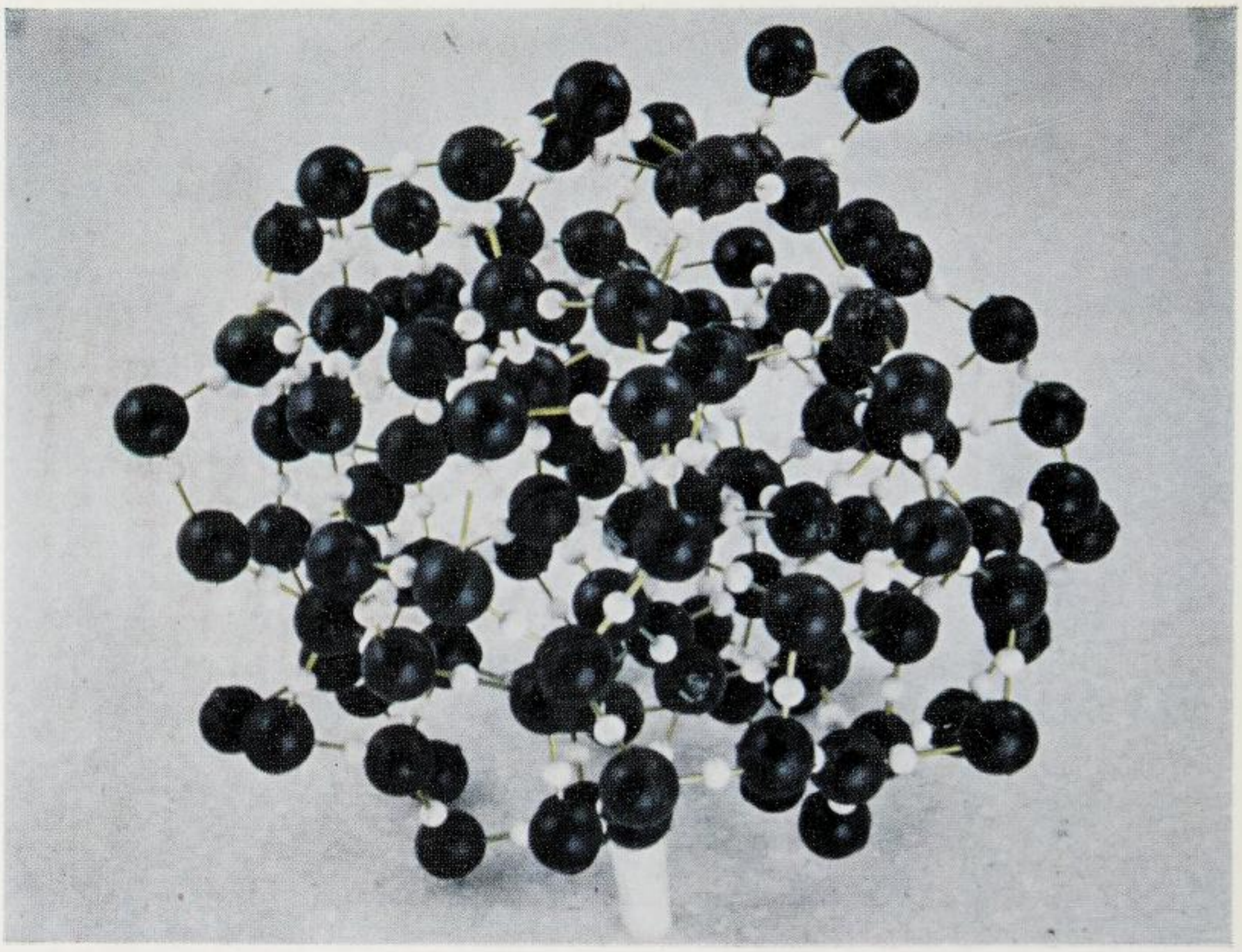
2



For explanation see p. 32.

PLATE 2

1



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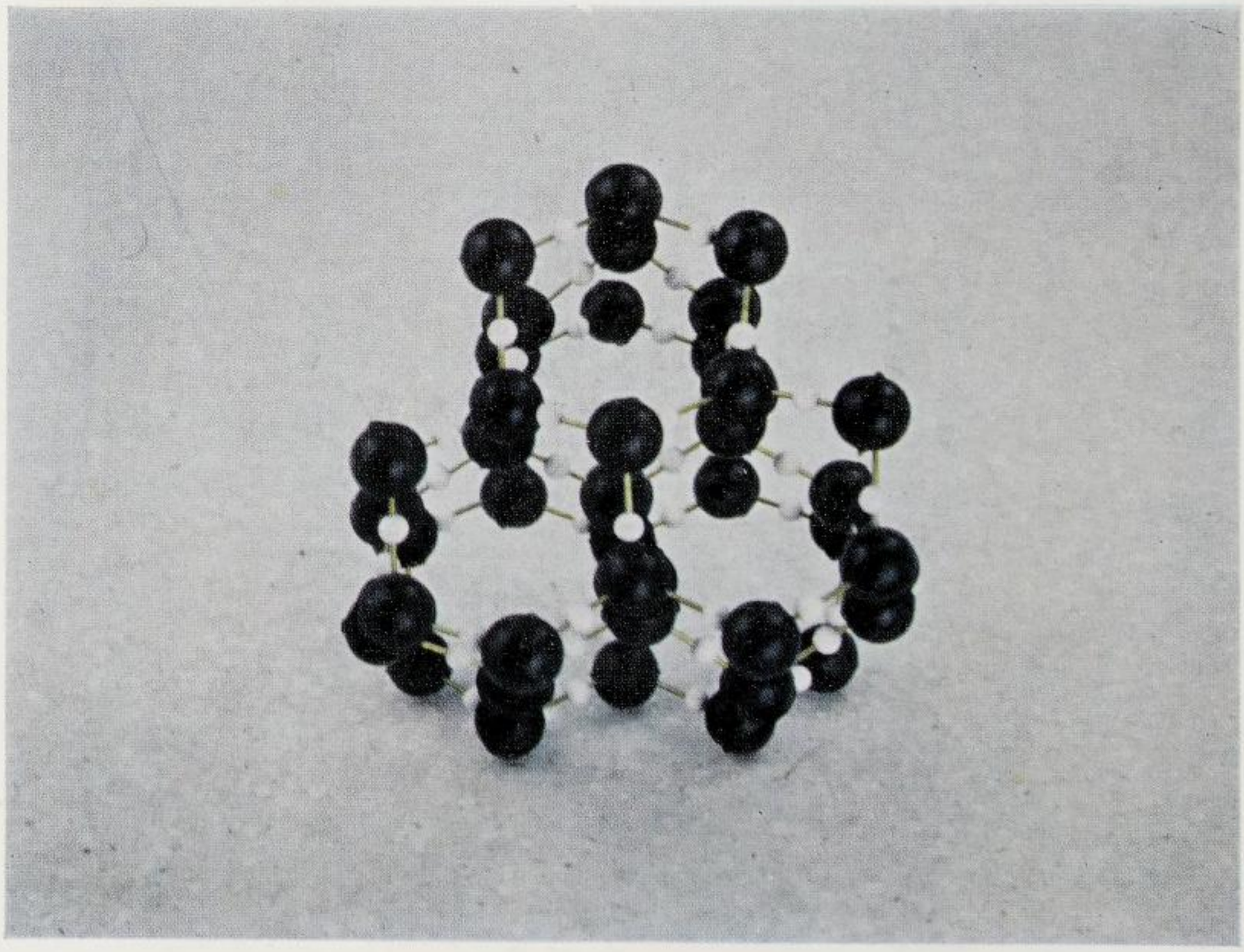
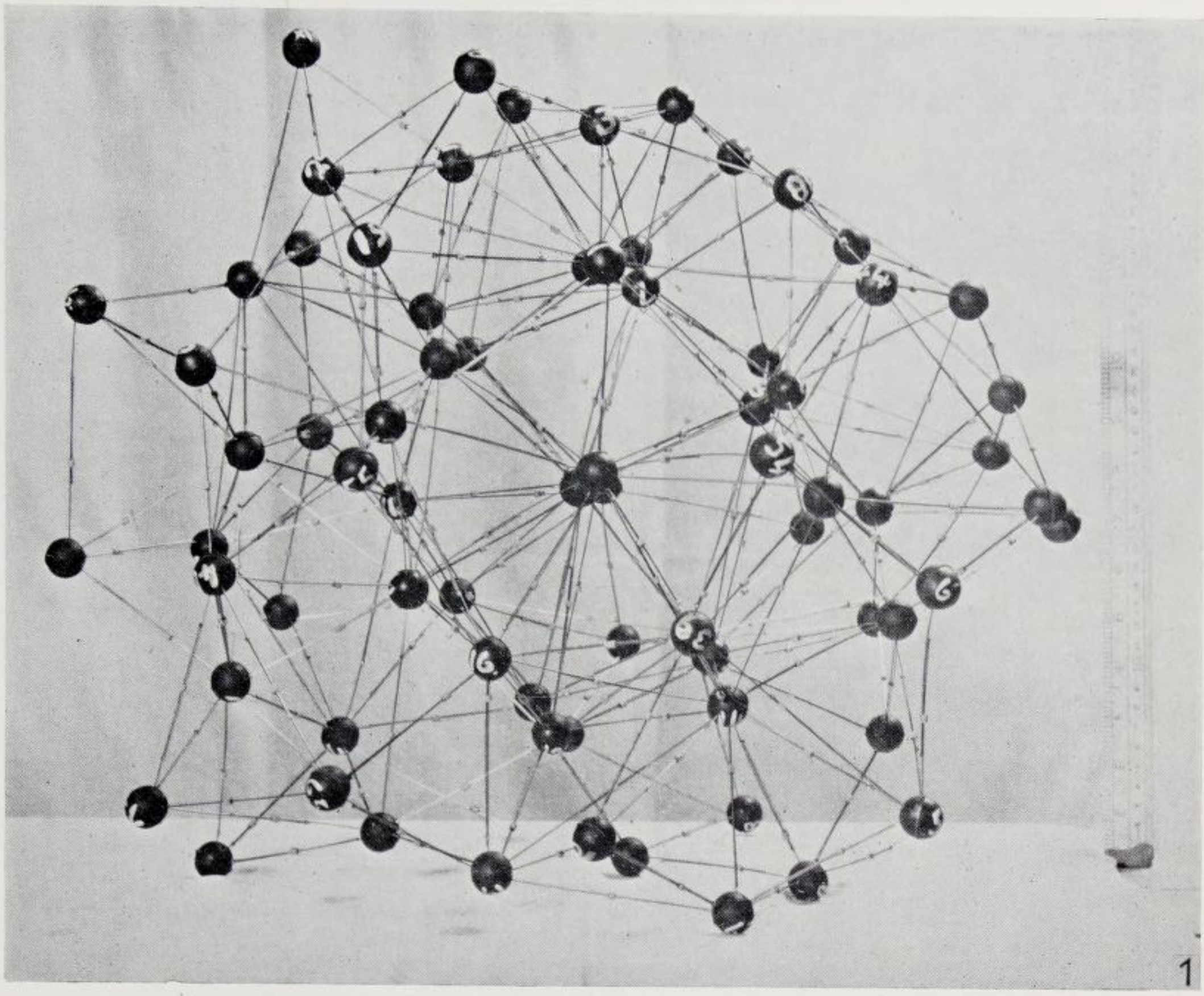
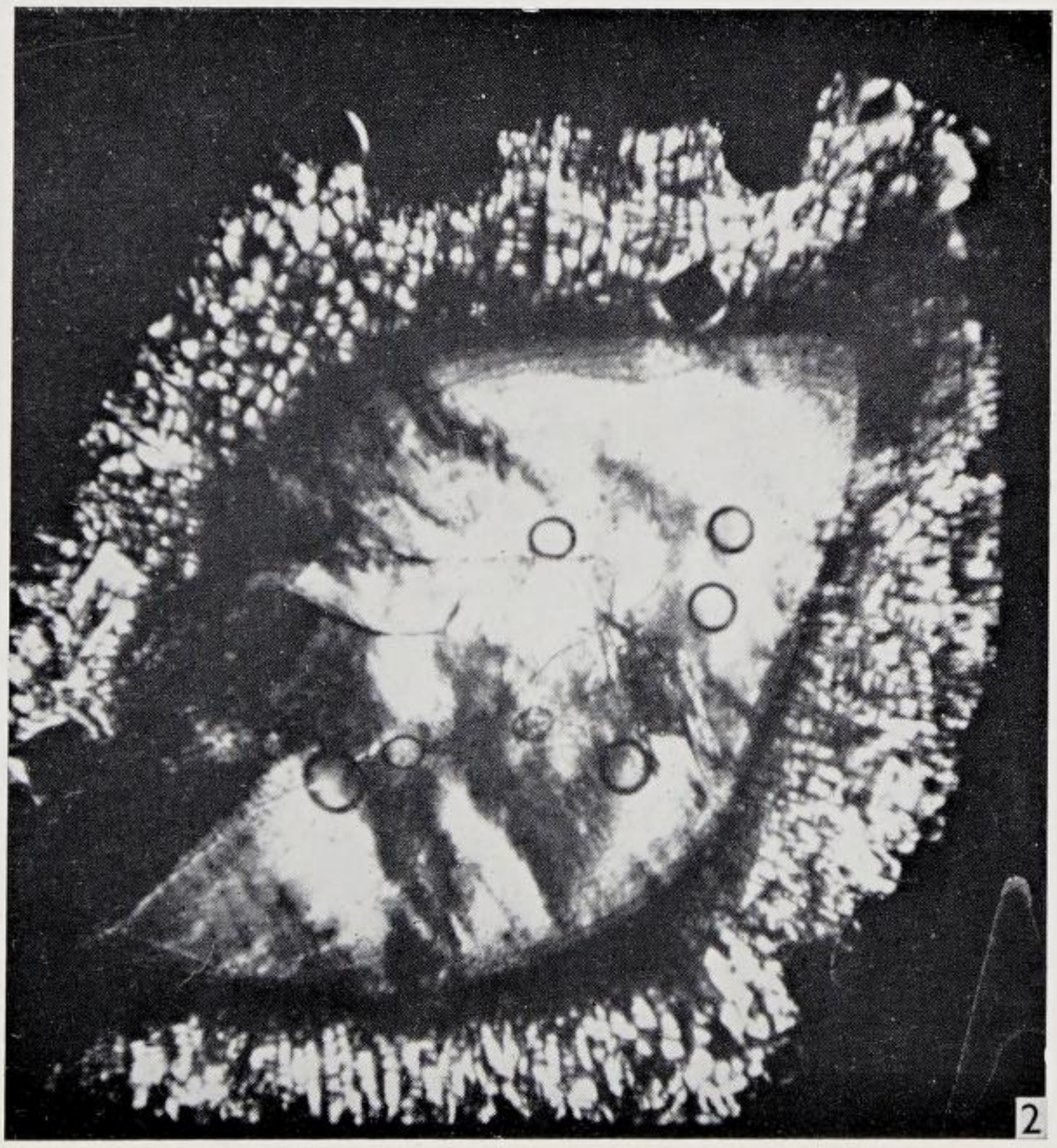
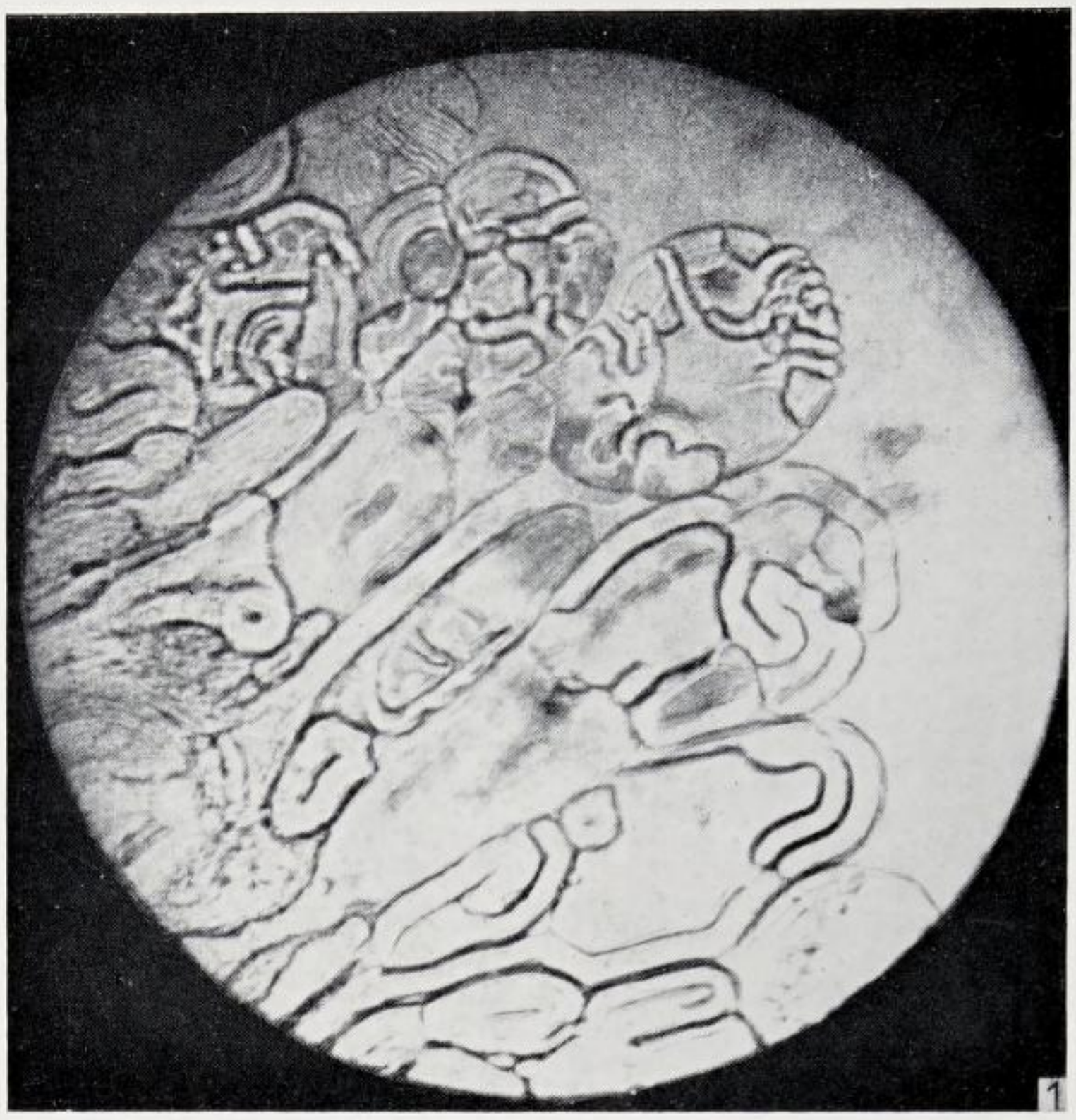


For explanation see p. 32.



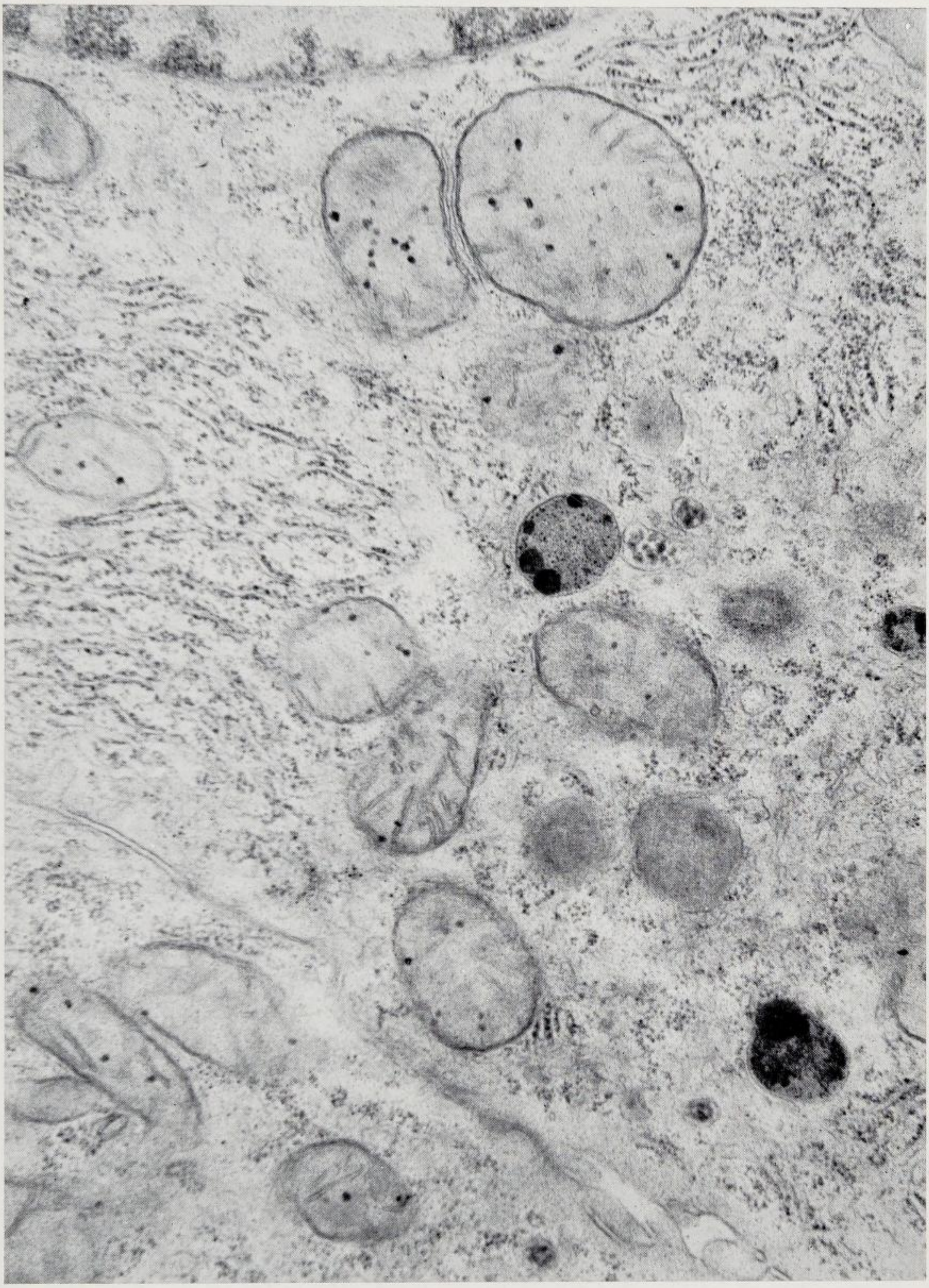


For explanation see p. 32.



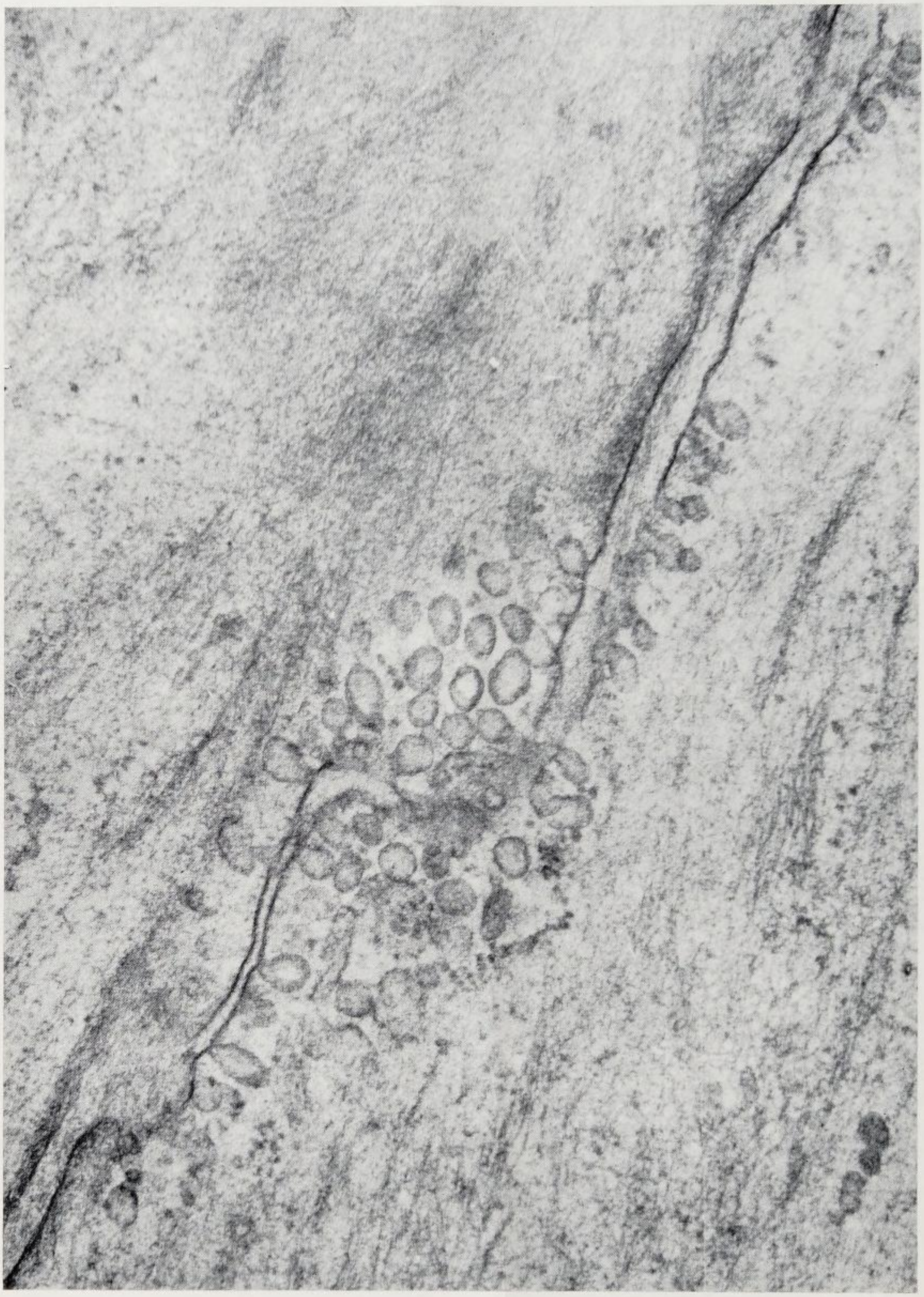
For explanation see p. 32.

PLATE 5



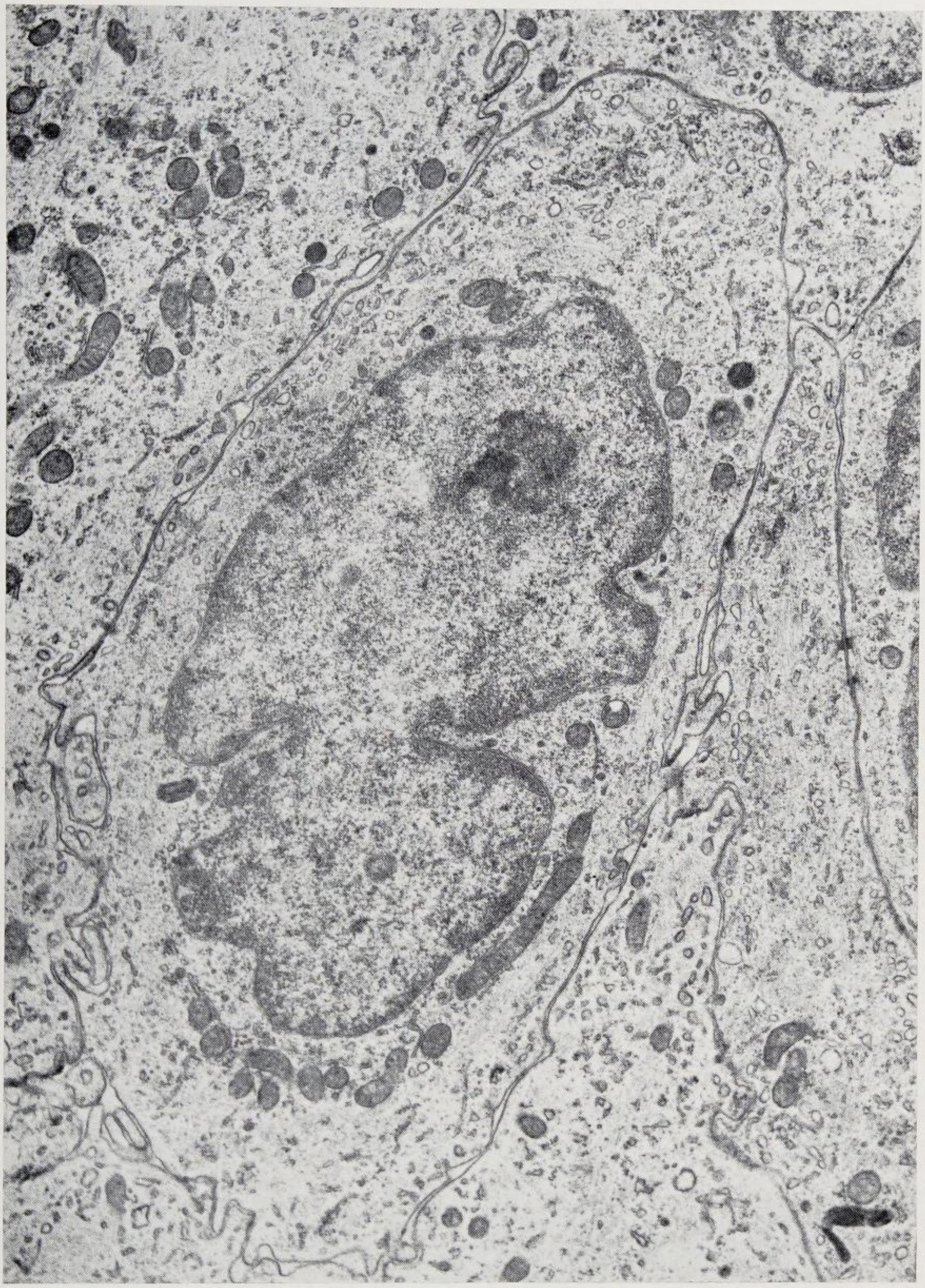
For explanation see p. 32.

PLATE 6



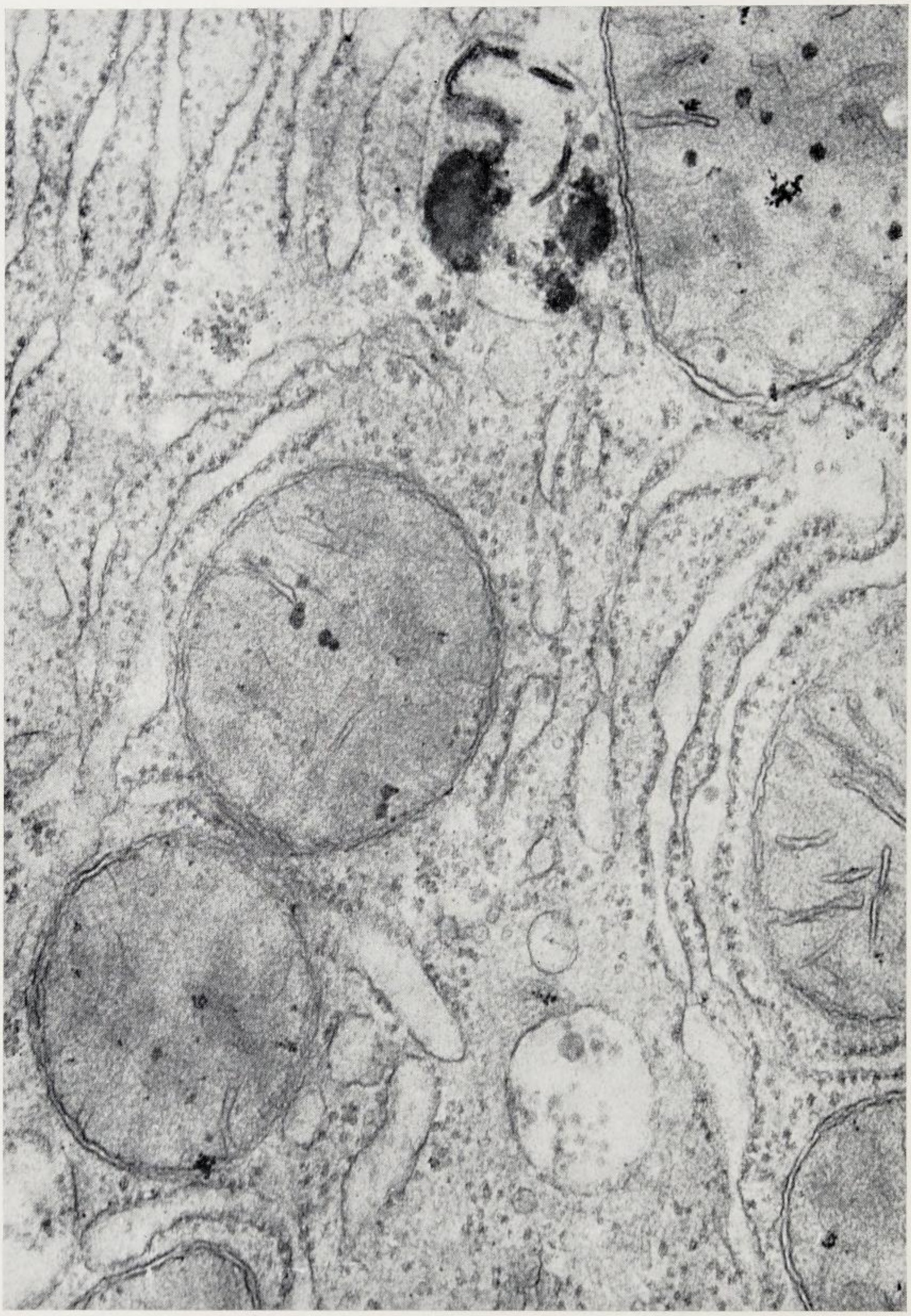
For explanation see p. 32.

PLATE 7



For explanation see p. 32.

PLATE 8



For explanation see p. 32.