

SCIENCE NEWS

EDITED BY A. W. HASLETT.

35

PENGUIN BOOKS

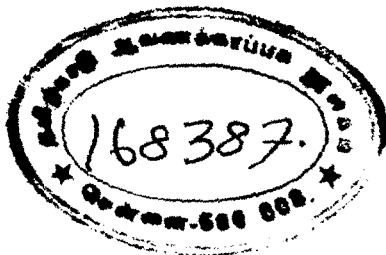
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CONTENTS

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EDITORIAL	7
HOW WE FORM CONCEPTS W. Mays	11
FINDING OUT ABOUT FUNDAMENTAL PARTICLES R. M. Tennent	24
MESON THEORY OF NUCLEAR FORCES G. Feldman	42
POLAROGRAPHY D. J. Ferrett	55
ADAPTATIONS IN DIVING MAMMALS R. J. Harrison	74
FREEZE-DRYING R. J. C. Harris	91
RESEARCH REPORT A. W. Haslett	108
CORRESPONDENCE	120
SOME BOOKS RECEIVED	122
ABOUT OUR CONTRIBUTORS	125
INDEX (COVERING NUMBERS 32-35)	127

19 illustrations are between pages 64 and 65

EDITORIAL

BOTH from inside science and from industry there come recurrent complaints of the inability of specialists to express their ideas and conclusions in forms intelligible to others. There is little difference in practice between the requirements of the so-called layman – who it is sometimes forgotten may be himself an expert in his own field – and that of the scientist working in some different branch of science. The difficulties are real to some extent. There are parts of physics where the language of the specialist seems no longer capable of translation. There is a gulf in chemistry between those who understand formulae and those who do not. In the descriptive sciences there is the difficulty that a descriptive term is a form of shorthand which can be expanded only by repeating the description in full or replacing it by a statement of origin or function, for which evidence may be lacking. But although the difficulties exist, they are not insuperable where there is a broad conclusion to be conveyed. Even in a difficult area it may be possible for a Nobel prize-winner to present his work in such a way as to make clear to an outsider what is its general object, the assumptions on which it is based, the nature of the argument, and the main achievement. This has been done in a first publication. To do it requires not only clarity of thinking and expression, but also courage. In order to say something simply, it is first necessary that one should, in a real sense, have something to say. Secondly, the simpler the statement, the more clearly exposed is any weakness or inadequacy. And, thirdly, there must usually be over-simplification in some degree. The first condition can be met by only a few people in original publications. The second and third call for a willingness to withstand the gibes of colleagues who prefer safety to communication. As was said some years ago by a newly elected Fellow of the Royal Society, 'the great thing about the Fellowship is that one is no longer afraid to make a fool of oneself'. There is, however, a more serious difficulty than fear of being laughed at. There is a widespread feeling, ex-

pressed often in conversation but seldom in print, that popular or semi-popular writing is an activity which should be indulged in only when the age of useful work is past. Not surprisingly, it does so happen that some of the best writing is done by those whose reputations are already made, who have learnt from teaching how little can be absorbed in one session, and who have suffered at meetings from those who proceed remorselessly with every last detail but omit any clear explanation of the main point. It is an illusion that there is any clear distinction between ability to explain at one level and ability to explain at another. There are merely those who can explain, and will, and those who cannot, or will not. Members of the second group are in the majority. They are dependent on the first group for the means to conduct research; since, unless its scope and purpose can be conveyed, means for its support will be lacking. And whatever impact it might have had will be delayed, whether in university or industry.

A sub-committee of the Royal Society wrote in 1950 that 'to most authors good writing comes only as a result of much practice. Experience shows that clarity and precision are best achieved by the use of short words and simple sentences'. Moreover, even for specialized journals, 'an author should write, not for the half-dozen people in the world specially interested in his line of work, but for the hundred or so who may be interested in some aspect of it if the paper is well written'. The latter comment may be supposed to refer to the many sub-divisions of work which exist within most subjects. Of interchange between subjects, Dr E. D. Adrian, the President of the Royal Society, said in his recent anniversary address that 'we still have a few who can survey the whole field and perhaps we never had more than a few, but certainly it becomes every day more difficult to find scientists whose interests are wide enough to assist the advance by helping specialists to understand one another'. The words 'to assist the advance' should be noticed; mutual communication is recognized not merely as an abstract ideal but also as a facility which is of advantage to science. Moreover, it appears to be tacitly assumed that the average specialist will be

incapable of acting as his own mouthpiece beyond the immediate circle of his fellows. The assumption is frightening, but is probably justified in the form stated. It follows, if true, that for the framing of decisions, whether in industry or by government departments, only the exceptional specialist will be of value.

The assumption that the specialist is unable to communicate is probably least true of the small minority of scientists whose work is truly creative. Yet there is here a valid reason for exceptions. New ideas do not always come easily or present themselves at once in their final form. A mental somersault may have to be turned, and a framework of thinking which has become a habit may have to be abandoned. Clarity is not then to be expected. If we ignore this case – which in the long run is the most interesting – we are left with a more readily appreciated group of researches which are seen at the time to open up a new range of discovery. In this situation the immediate innovators are busy people; they are badly placed to undertake the more general reviews which are necessary if others beyond the immediate circle are to be interested. But, in fact, it is not among these men that the attitude already mentioned is most commonly to be found. Whether from the interest of what they are doing, or from appreciation of the need for wider communications in science, such men are usually willing in principle to give the sort of account which will be helpful to others. They do not regard it as an activity to be deferred until retirement is approaching, and, if writing of this kind tends often to be postponed, it is from competition with other activities.

The average research worker is not an originator in this sense. He contributes relatively small items to the total pool, and these items are commonly of the same kind as those already supplied by others and are obtained by the use of previously used methods. He is saved from being a technician to the extent that his own contributions are related to problems and knowledge in a wider area. The writing of an article is itself a help to this end. It encourages a more lively approach to the literature than would otherwise be made, and compels the sort of questions that should be asked if new experiments are to be suggested. 'It all

seems much clearer to me now', was the comment of one author who had lately, and with much pain, completed an article.

An important special case is that of the relatively junior research worker who is discovered to have a talent for explanation, and with it some critical faculty. Neither of these qualities is connected necessarily with originality in research. They are, in their own right, useful qualities which should be cultivated. It is in this context that an attitude of superiority on the part of others is most strongly to be deprecated. Because a man can explain, and will, he cannot be worse as a research worker; he may, on the contrary, be better. In any case, he possesses qualities which his critics either do not possess or are unwilling to use. To the head of his department it should be cause for encouragement that someone has been found to take over part of the work of communication. In some departments and laboratories, this is so already; unfortunately, it is not so in all.

Finally, there is an objection which is often advanced to the translation of technical terms into others which can be understood with less effort by more people. This is a common requirement in *Science News* in the case of terms which are encountered only casually in the course of an article, and which it is therefore not worth while to establish. In more acute form it arises in almost any kind of report intended for readers without previous knowledge of science. The meaning of the correct terms, it is sometimes said, can be discovered from standard works, and it can be left to the user to translate. The question is, then, not whether translation is necessary, but who should do it: whether someone who knows his subject, or someone who does not. Logically, only one answer seems possible. But it is not always the answer given.

HOW WE FORM CONCEPTS

W. MAYS

THE picture which the Western adult presents to himself of the world around him makes use of abstract concepts, which are also used in science. Some of them go back to the beginnings of civilization. For example, the concepts of weight, volume, number, and length are necessary for the invention of weights and measures. So, too, is the concept of causality: for, unless the same procedure applied under the same conditions is recognized to lead to the same results on all occasions, systematic measurement is meaningless. Other concepts such as an invariant space and time may be thought *a priori* to imply a higher degree of sophistication. The development of these concepts in the individual has been studied by Jean Piaget, Professor of Psychology at the Universities of Paris and Geneva, from about 1921 onwards. His work is of interest from two different points of view. From that of the psychologist, a knowledge of the normal process of concept formation in the individual is likely to be of help in understanding the abnormal adult, in whom that process has either not been completed or undergone a devolution. From the point of view of the philosopher of science, the origin of concepts which have been so widely used in science is clearly important. Piaget has, in fact, shown that the space, time, and causality of physics are all adult conceptions; and that the conceptual apparatus by means of which the child orders the world around him is of a much more naïve variety than had previously been suspected. From about 1939 onwards Piaget has introduced new experimental techniques for studying the development of specific logical, mathematical, and physical concepts. But until about a year or two ago, this more recent work was curiously neglected by other psychologists.

In his early work Piaget was largely concerned with investi-

gating the various kinds of thought activity entering into the intelligent behaviour of the child. Unlike the intelligence tester he was not primarily concerned in giving a quantitative evaluation of their behavioural outcome. For Piaget the method of intelligence testing as a tool for investigating child thought suffers from two defects. The first is that the test questions and the conditions under which the test is given are stereotyped in character; the second that the use of a fixed questionnaire neglects the spontaneous answers of the child. Piaget's method, on the other hand, resembles that of the clinical psychologist, since he attempts to make the child talk freely, varying the question according to the situation. He is also much more interested in finding the reasons why children give the answers they do to the test questions. From these researches Piaget concluded that up to about 7 to 8 years of age, the child tends to think in a fragmentary manner and to argue from particular to particular. In children's drawings, for example, where there is an inability to understand the relations of part and whole, pieces of one and the same whole may be juxtaposed. In drawing a man the child may draw an eye alongside a head, or a nose where an ear ought to be. He has also difficulty in coping with syllogistic and analytic reasoning since it assumes the ability to select and eliminate. Further, children's concepts have a certain viscosity about them and tend to vary throughout a reasoning process.

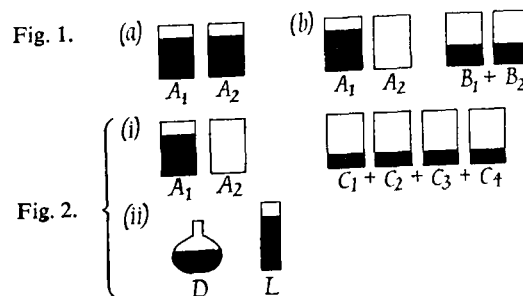
Piaget as we have noted has now followed up this earlier work by carrying out detailed experimental studies on the development of such concepts as quantity, number, weight, volume, time, and space. The subjects used in these experiments were children aged 4 to 12 observed individually. The experimenter performs in front of them experiments on familiar objects, and they are asked to predict their outcome. In order to find out how they interpret these experiments further questions are put to them. Piaget groups the answers to the various questions into three types according to whether or not the child recognizes the conservation of the concept concerned, whether it be quantity, weight, number, etc.; these types are not restricted to precise age-levels. They are:

- (i) absence of conservation (4-6 years *on the average*),
 - (ii) intermediary reactions (6-7 years *on the average*),
 - (iii) necessary conservation (7- years *on the average*);
- (ii) only occurs in some children; in others there is a direct transition from (i) to (iii).

THE CONCEPT OF QUANTITY

It will be of help to describe some of Piaget's experiments. In this way we shall obtain some idea of the new kinds of techniques he has introduced into his studies of child thought. We will start with a discussion of the conservation of quantity.

Two identical vessels A_1 and A_2 are filled to the same level with a coloured liquid (orangeade). The experimenter then pours half of the contents of A_2 into a vessel B_1 and the other half into a vessel B_2 , both of these the same shape and size as A_2 .



(Figure 1). The child is then asked if the quantity of liquid in A_1 , which retains its original level and that in B_1 and B_2 (derived from A_2) remain the same. Young children (stage i) assert that the quantities are now unequal; some note that the levels of B_1 and B_2 are lower than that of A_1 , whilst others who note that the liquid is now divided between two containers, believe that B_1 and B_2 contain together more than A_1 . Children thus concentrate on specific visual aspects; either on the number of containers, their level, or cross-section, and do not consider them in relation to one another. The quantity of liquid increases or diminishes for them according to the size or number of the

containers. They are unable to grasp that an increase in the height of the liquid is compensated by a diminution in cross-section, that these two quantities are inversely proportional.

Though children at the second stage affirm conservation, they do not do so in every case. They may, for example, agree that the liquid poured from A_2 into B_1 and B_2 conserves its quantity, but they will hesitate if the same liquid is divided between four vessels (C_1, C_2, C_3, C_4) or if it is poured from a vessel D into a narrower vessel L (Figure 2). The child who accepts conservation when differences in level, cross-section are slight, begins to doubt it when the differences are greater. At the third stage, however, he admits conservation in every case.

It might be objected that in the above examples the child has not understood that the question refers to the liquid as a whole; that in effect he simply compares one level with another; one cross-section with another, etc. But this, the objector may go on, does not mean that the child is unable to make accurate quantitative judgements, he merely speaks a different language from us. He may not have the necessary vocabulary at his disposal to make this distinction. Nevertheless, Piaget points out, if the child gives a correct reply when the variations are slight, but hesitates when the variations are greater, he would appear to understand the question but is unconvinced that the quantity always remains constant.

How does the concept of 'conservation of quantity' develop? At first, as we have seen, such judgements depend only on particular visual aspects, either the difference in the number of containers, level, or cross-section. This conception is only arrived at by the child when he is able to return to the initial state by an inverse operation. For example, when he knows how to restore the original state of the liquid by pouring the contents of B_1 and B_2 into A_2 . For Piaget 'reversibility' is a fundamental characteristic of thought and is essential for any form of mental experimentation, and also for logical inference. For any set of activities one is able to produce conceptually a corresponding reverse procedure. In logic, too, one can proceed from conclusion to premises as well as from premises to conclusion. Thus

at the third stage the child spontaneously asserts that such procedures are always reversible. 'Conservation' implies what Piaget calls the 'coordination of differences' (or proportions), for example, that the diminution in height of the level of the liquid poured into B_1 and B_2 is compensated by an increase in the number of containers. The child is now able to grasp the concept of an invariant quantity of liquid; which in this experiment is the logical product of the height and number of containers, or of height and cross-section. In other words, he is able to think away the visual qualities and concentrate on the logical relationships involved. Extensive quantification (as opposed to qualitative judgements) begins when the child grasps that these differences compensate each other.

Similar experiments may be carried out with solids; two balls of modelling clay of equal size are shown to the child, both of which he recognizes as containing the same amount of clay. One of the balls is then flattened so as to take on the form of either a pancake or a sausage. At first the child does not admit 'conservation of quantity'. He may say the pancake contains more clay than the ball, and the sausage more than the pancake, etc. At the second stage he recognizes conservation in some cases and rejects it in others; finally at the third stage he always admits conservation.

It may be said that the experiments on liquids and clay are ill adapted to suggest the 'principle of conservation' to young children, since the division of continuous quantities into units present a natural difficulty. To test this Piaget carried out a further series of experiments with discrete quantities, for example, collections of beads. The two vessels A_1 and A_2 of the preceding experiments are filled with beads. When the beads are poured as before from A_2 into different vessels (B_1, B_2) similar in shape and size, the identity ceases to hold for the younger children. The experiment may be varied and the child may be asked to put a bead in a narrower vessel L each time the experimenter puts one in the wider vessel D , such that two equal collections are formed. Even though the child has established this term-to-term correspondence himself, the collections are nevertheless said to

be unequal when he observes that their levels are different. Finally, he affirms conservation and justifies it by the concepts of 'reversibility' and 'compensation'. He will say that if the beads in *L* and *D* are interchanged, they will retain their original levels; and he will at the same time point out that the increase in level in *L* is compensated by an increase in width in *D*.

NUMBER

The way in which the child arrives at the notion of number is covered by a new series of experiments; the child has to establish a term-to-term correspondence between different collections of objects. For example, he has to form a row of glasses parallel to a row of regularly spaced bottles (one glass in front of each bottle), or he has to put a flower in front of a vase. To take another example, when a child aged 4 to 5 is asked to spread out on a table as many red counters as there are in a spaced out row of six blue counters, he begins by making a row of the same length, relying exclusively upon perceptual criteria. However, if the counters forming one of the two rows are spaced out or closed up a little, he will now believe that the row with the greater length contains more members. If the child is asked to make the rows equal, he may either increase the intervals of the row which appears to him as deficient, or add new elements to it. Number and space are as yet undifferentiated for him, they form a perceptual whole. But once the numerical correspondence has been established it remains constant. If the intervals of the row are changed, or if the counters are put into a heap, he will now assert that there is no change in number. In other words, the changes have now become reversible. The child is aware that the increase in the length of the row is proportional to the increase of the intervals between the counters, and that re-establishing the original intervals entails re-establishing the original length of the row.

SUBSTANCE, WEIGHT, AND VOLUME

Returning to experiments on liquids and deformed balls of clay, the child at about 7 to 8 accepts the principle of 'conservation of

quantity', which Piaget terms substance, but he will only agree to the conservation of such concepts as 'weight' and 'volume' at a later date. The first concept which differentiates itself from that of 'substance' is 'weight'. Children are asked to compare the clay objects, the ball, the pancake, the sausage, etc., from the point of view of their weight, i.e. whether they are heavy, light, etc. Now children who grasp the 'conservation of substance', still deny 'conservation of weight'; they will say that the pancake contains as much clay as the ball, but it is less heavy. The notion of weight, Piaget points out, is difficult to abstract from its subjective components, since in objects of equal weight the sensations of pressure are not always the same. Children are surprised when they discover by means of a balance that the ball and the pancake weigh the same. 'Conservation of weight' only appears when these apparent variations are held to be subjective.

Similar difficulties are found in the case of the notion of volume. Water is put into a glass, and the level of the water is marked on the outside. The child is then asked to predict what will happen to the level if a ball is immersed in the water. Between 5 and 8 years he does not expect the level to rise, and he is surprised when it does, since he is unable to grasp that the volume of the ball is added to that of the liquid. And this may be observed among children who already admit the 'conservation of substance' and 'weight'. It is still more difficult for them to understand how a piece of sugar dissolved in water can make the level of the water rise. Piaget points out that the 'conservation of volume' implies something like the concept of a generalized atomic structure; in this case, the permanence of little invisible elements which separate out in the solution and retain their independence, and this is only acquired after the age of 10. Conservation of substance normally appears at 7 to 8, conservation of weight at 9 to 11, and conservation of volume at 11 to 12.

TIME, MOVEMENT, AND SPEED

Philosophers such as Kant have believed that the categories of space and time were immediate objects of an *a priori* intuition.

Piaget proceeds to see whether this is really the case, or whether these concepts have gone through a similar process of development. Has the child an immediate intuition of time? Despite the Kantians the abstract concept of time would seem to arise at a relatively late stage in the child's thought, since time at first remains confused with space. Piaget demonstrates this by a further series of experiments.

For example, two dolls on a table are made to move along two equal parallel lines at different speeds; the slower of the two continues to move a moment after the faster (which has passed it) has stopped. The child will deny that one has taken longer to travel through the same distance than the other. He will say they have taken the same time, since the fact that the distances are equal tends to mislead him. The child is unable to differentiate distance run through from time. This only becomes possible when he is able to extrapolate conceptually the movement of the faster object, noting that it would have gone past the slower one if it had not stopped. Similarly, if equal quantities of water are allowed to run into two differently shaped vessels (one pear-shaped and the other spherical), though the child has observed that the recipient vessels have started and completed filling at the same time, he will, nevertheless, disbelieve that their time of filling is the same. If the level of the water in one vessel appears higher than the other, he will assert that it has taken longer to fill. The child will only be able to estimate time objectively when he no longer judges it simply by the increase in the level of the water, but by the increase in level in relation to the dimensions of the recipient vessel; in other words, when he is able to multiply logically these two variables.

But it may be said, have we not an immediate intuition of time independently of our construction of physical time? According to Piaget, our everyday notion of time is constructed in a similar way. The child at first confuses the notion of age with that of height or other visible signs of ageing. Age differences are not thought of as constants, the young can overtake the old. A child born at a later date than another may outpace him if he out-

grows the latter. If the growth of two trees (e.g. an apple and a pear tree) is represented by drawings, then the child will state that the pear tree planted later than the apple tree is younger to start off with, but that if it grows more it will become older. Piaget's experiments further show that young children evaluate the time of their own actions by work done. If two actions occur in two equal periods of time, but one is more rapid than the other, children will say the former takes longer to occur. Older children are able to correct their time judgements by distinguishing between subjective and objective time. Objective time also assumes the concept of reversibility, since it involves the ability to reverse the course of events in thought.

Since time has a complex character Piaget proceeds to study the more concrete notions of movement and speed, since he thinks that psychologically they are prior to the notions of time and space. Consider, for example, the primitive intuition of 'speed'; if two objects move parallel to each other, the faster will pass the other. But since for the child speed remains as yet unrelated to the space run through, if he sees the beginnings and ends of the paths, but the rest of the paths (which are unequal) are made under cardboard tunnels, he will say that the two objects have the same speed (Figure 3a). Similarly, in the case of two visible paths; for example, when one object runs through one side of a triangle, whilst the second (faster one) runs through the other two sides so that they reach the same end-point at the same time, their speeds are judged to be equal (Figure 3b). Or to take another example, if two objects move along two parallel straight paths, and the faster one coming from further off overtakes the other and both stop at the same time, he again judges the two speeds as equal. At a later date the child will, however,

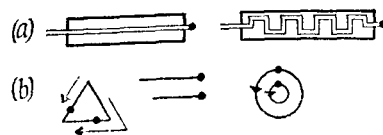


Fig. 3.

be able to rectify his evaluation of 'speed', since he will now grasp that the faster object would have gone past the slower one if it had not stopped.

IDEAS ABOUT SPACE

We come now to consider space: is it given to us as a simple intuition or does it, too, arise as a result of a process of development? Historically, Piaget points out, geometry has developed in several stages. First there arose classical three-dimensional Euclidean geometry, later projective geometry, and finally topology. Piaget finds that the development of the 'concept of space' is made in the child in the reverse order. He starts with purely topological notions, continues with projective notions, and finally arrives at those dealing with the shape and size of the object. At the age of three the child can, for example, distinguish between open and closed figures. If, however, he is asked to copy a circle, a triangle, or rectangle, he draws in each case a similar closed figure (Figure 4). The child can do this before he can draw a rectangle and express its Euclidean characteristics (number of sides, angles, etc.). Piaget points out that, curiously enough, the psychological order of development is much closer to modern geometry's order of deductive or axiomatic construction than the historical order of discovery was.



Fig. 4.

In projective space, one is concerned with linear transformations. At first the child has difficulty in representing a straight line. Later on, if he is asked to arrange a line of matches (stuck in little blocks of plasticine) diagonally across a table, he may start building the line parallel to the table's edge, and then proceed to change the direction and form a curve to reach the other end. After the age of 7 the child grasps that the projective relationship depends on the angle of vision, and he may actually sight along the line to see whether it is straight. If a child is asked to draw a pencil tilted at different angles, as he actually sees it,

he asserts at first that he always sees it as having the same length, and indeed always draws it thus. A similar state of affairs is observed when he has to predict what will be the shadow of the pencil (tilted in these different ways) when it is projected on the wall.

The following experiment is used by Piaget to enable him to study the coordination of perspectives. The child is seated facing a rough model formed by three cardboard mountains of different colours and heights, arranged in a triangle. He is required to understand how a doll moving round the mountains to the left, behind, to the right of the model sees them, and he has to select from photographs of the model (taken from different points of view) that photograph corresponding to the point of view of the doll. Or conversely, given a photograph to discover the point of view from which it has been taken. At first the child is incapable of imagining a perspective other than his own, since he has no conception of perspective, as this implies an ability to conceive other points of view. Small children remain tied to their own particular point of view, even though they have previously walked round the table. In effect, the child says, the same thing is seen at any place, the mountains as he sees them are 'the mountains as they really are'. He learns little by little to make relational judgements, 'this mountain is in front of that', 'this behind that', etc. Finally, he becomes able to take account of several relations at a time (before, behind, right, and left, etc.) and to coordinate them into a general system of perspectives.

This brings us to the metric representation of space. In the adult this results from a system of horizontal and vertical axes, which seem to be based on postural reflexes. To study its development Piaget performs the following experiments. After the child has been shown the level of the water in an inclined test tube, he is asked to draw its level on a standard drawing. For quite a lengthy period of time he draws a line parallel to the bottom of the tube; and he is surprised when he discovers by being made to hold a pencil to the surface of the water that it remains 'stationary' when the tube is tilted. In other words, the child has not yet constructed conceptually an independent

horizontal plane. Similarly, with the vertical plane, if the child is made to draw men, trees, and houses, on the slope of a mountain, he represents them as perpendicular to the inclined surface of the soil. The conceptual system of horizontal and vertical axes is not therefore a primitive property, but arises once again as the result of a complex coordination of relationships.

CONCLUSION

A frequent objection to Piaget's work is the absence from it of statistics. It is often asked how many children has Piaget experimented on, and on how many different groups and in how many different places have his experiments been repeated. Piaget's method is, of course, the intensive study of a few cases, rather than the statistical investigation of a few traits in a large number of cases, but even then his studies cover many thousands of children. It is true that as far as his early studies are concerned, his results have not always been verified. Obviously this indicates that further work needs to be done on these lines. To the objection that rational activity is found at a much earlier stage than he at first admitted, Piaget now distinguishes between intelligent activities as they occur on a behavioural level in the young child and the later operations of conceptual thought.

As far as his more recent work is concerned, psychologists have not, as we have seen, taken much notice of it, let alone having made any attempt to repeat his experiments. Piaget would be the first to admit that his work needs to be regarded more as a pilot experiment, in which considerably more experimentation and thinking is required. He has at least traced out the lines of investigation on which we should proceed if we wish to obtain a picture of child thought. And Piaget contends that such an investigation may help to illuminate not only adult thinking but also pathological thought. Some of Piaget's more recent researches have already found an application in the study of mentally deficient children. The degree of impairment of the child's capacity to form such concepts as quantity, weight, volume, etc., gives a measure of his degree of mental defect.

FURTHER READING

For Piaget's early work on verbal reasoning the following of his books may be consulted.

The Language and Thought of the Child. London, Routledge and Kegan Paul, 1924.

Judgment and Reasoning in the Child. London, Routledge and Kegan Paul, 1924.

The Child's Conception of the World. London, Routledge and Kegan Paul, 1926.

The Child's Conception of Causality. London, Routledge and Kegan Paul, 1927.

For his more recent work on concept formation see his books:

The Psychology of Intelligence. London, Routledge and Kegan Paul, 1950.

The Child's Conception of Number. London, Routledge and Kegan Paul, 1952.

A summary of this work is given in:

Piaget, Jean. *Logic and Psychology*, Manchester University Press, 1953.

Further translations are being published by Routledge and Kegan Paul.

FINDING OUT ABOUT FUNDAMENTAL PARTICLES

R. M. TENNENT

SOME of the most interesting research of the past decade has been concerned with the nature and behaviour of the constituents of atomic nuclei. In the early 1930s, the existence of the proton, the neutron, and the electron was established and it was known that an atom was made up of a combination of protons and neutrons forming the nucleus, with sufficient electrons circling round the nucleus to balance the electric charge. Protons, neutrons, and electrons are household words now and may frequently be met with in the course of popular reading. Recently, new words - 'meson' and 'hyperon' - have been added to the scientific jargon creeping into common usage. Let us clear our minds as to these different particles and then see how the hard-won information on the subject of 'Particle Physics' has been acquired.

Table I on page 26 shows a list of the established fundamental particles with their characteristics as known at the time of writing. Ignoring, for the moment, the neutrino, there are twelve particles with masses ranging from the electron with mass 1 unit, through the mesons and nucleons to the hyperons which are about 2,300 times as heavy as the electron. As far as is known, the proton and neutron are the 'bricks' with which nuclei are built, while the mesons form the 'mortar' which holds them together. There is evidence that the hyperons are excited nucleons, that is to say, nucleons which have more energy than they can contain for any length of time.

The most fruitful source of fundamental particles has been the cosmic radiation. The primary cosmic radiation consists of

energetic protons, and heavier atomic nuclei. When these fast-moving particles reach the earth's atmosphere, they hit nuclei of nitrogen or oxygen and produce mesons and hyperons. The secondary particles travel on in the path of the initial radiation and a chain of events is set up resulting in the radiation which strikes the earth's surface.

When it was known, from observations on cosmic rays, that mesons were produced when protons struck atomic nuclei, efforts were directed towards building machines which would accelerate protons to energies sufficient for the process. As a result, artificially produced mesons are available in various laboratories - mostly in the United States of America. The energy required for meson production is proportional to the mass of the meson wanted. Artificially produced *L*-mesons (the lighter ones) have been available for several years now, and production of *K*-mesons has recently become possible with the latest accelerators.

All the fundamental particles are unstable except the proton and the electron. This means that they cannot exist indefinitely, but change their nature. The neutron with a mean lifetime of 13 minutes is the longest-lived of these particles (apart, of course, from the electron and proton). At the other end of the scale are the *K*-mesons which can only exist for about 10^{-9} sec. before decaying. We see then how difficult it must be to gather information about particles which are so small as to be invisible, are so light that weighing them by ordinary means is impossible, and which exist only for times of the order of microseconds.

Fundamental particles being 'simple' forms of matter can be described in terms of five constants. That is, if the five constants of a particular particle are known, they provide sufficient data for a prediction of the particle's behaviour under most circumstances. It is meaningless to try and measure the shape, colour, or texture of a particle, because these concepts have no significance in a realm where the Heisenberg uncertainty principle holds sway. The five important constants are mass, electric charge, mean lifetime before decay, spin, and magnetic moment. A large proportion of physical research has

TABLE 1: Characteristics of the Established Fundamental Particles

Family	Name	Symbol	Mass	Spin	Lifetime	Decay scheme
—	Neutrino	ν	0	$\frac{1}{2}$	?	?
Electrons	Electron Positron	e^- e^+	1	$\frac{1}{2}$	∞	stable
L-mesons	Mu-meson	$\mu^\pm$	207.0 ± 0.4	$\frac{1}{2}$	$(2.22 \pm 0.02) \times 10^{-6}$ sec.	$\mu^\pm \rightarrow e^\pm + \nu + \bar{\nu}$
	Pi-meson	$\pi^\pm$	273.0 ± 0.4	1	$(2.53 \pm 0.1) \times 10^{-8}$ sec.	$\pi^\pm \rightarrow \mu^\pm + \nu$
	Neutral pi-meson	π^0	264 ± 1	1	about 3×10^{-14} sec.	$\pi^0 \rightarrow \gamma + \gamma$ or $\pi^0 \rightarrow e^+ + e^-$
K-mesons	Tau-meson	τ	965 ± 3	integral	about 5×10^{-9} sec.	$\tau^\pm \rightarrow \pi^\pm + \pi^\mp + \pi^\pm + \pi^\mp$
	Theta-meson	θ	970 ± 10	integral	$(1.2 \pm 0.8) \times 10^{-10}$ sec.	$\theta^0 \rightarrow \pi^+ + \pi^-$
	Kappa-meson	κ	about 1000	?	?	$\kappa^\pm \rightarrow \mu^\pm + \gamma^0 + \gamma^0$
	Chi-meson	χ	about 1000	?	?	$\chi^\pm \rightarrow \pi^\pm + \gamma^0$
Nucleons	Proton	p	1836.13 ± 0.04	$\frac{1}{2}$	∞	stable
	Neutron	n	1838.66 ± 0.04	$\frac{1}{2}$	(13 ± 3) mins.	$n \rightarrow p + e^- + \bar{\nu}$
Hyperons	Omega particle	$\Omega^\pm$	about 2300	$\frac{1}{2}$ -integral	?	$\Lambda^\pm \rightarrow n + \pi^\pm$
	Neutral lambda particle	Λ^0	2181 ± 1	$\frac{1}{2}$ -integral	$(3.7 \pm 0.5) \times 10^{-10}$ sec.	$\Lambda^0 \rightarrow p + \pi^-$

been devoted to finding the values of these quantities for the different particles which exist.

The mass of a particle is akin to its heaviness. It is measured in grammes or, more commonly (as in Table 1), in multiples of the mass of the electron. The fundamental particles have been divided into groups according to their masses. Thus there are electrons, L-mesons, K-mesons, nucleons, and hyperons. Within each group there are particles with different masses. Cosmic-ray particles frequently travel at speeds approaching that of light so that their masses are increased, as predicted by the Special Theory of Relativity, because of the great energy they have. The mass of a particle travelling at speed v is $m_0/\sqrt{1-v^2/c^2}$ where c is the velocity of light and m_0 is the mass of the particle at rest, commonly called its 'rest mass'. On this account, mass measurements made on particles travelling through the detector at great speeds are usually converted to yield rest masses, as the mass of a fast-moving particle has no meaning unless its velocity is known.

All the fundamental particles have either unit charge or zero charge. The charged particles can usually exist in both positively-charged and negatively-charged forms. It has been shown that the charges carried by the different particles are equal (with very small limits) to that carried by the electron. The magnitude of the electronic charge is known very accurately from experiments made by R. A. Millikan in 1917.

The mean lifetime of a given particle is the average time for which particles of that type exist before decaying. Unstable particles may be imagined as parcels of matter which have been insecurely tied up. It is only a matter of time before the 'string will break' and the parcel burst asunder — or the particle decay. The time before the decay occurs follows an exponential law; that is, the probability of the decay occurring between times t and $t + \delta t$ is proportional to $\delta t \cdot e^{-t/T_0}$. The average time before decay is T_0 , which is the mean lifetime of the particle as already mentioned. Once again, the special theory of relativity tells us to be careful if the particle is moving quickly. At a velocity v , the mean lifetime of a particle is increased to $T_0/\sqrt{1-v^2/c^2}$.

The lifetime of a particle is thus increased in the same ratio as its mass, and as with masses, lifetimes are quoted for the particle at rest.

The 'spin' of a particle is its inherent angular momentum and may be considered as due to its spinning about its own axis. Its value is necessary for a theoretical analysis and is usually inferred from the particle's behaviour rather than being measured directly. The magnetic moment determines the torque acting on the particle when in a magnetic field. As for spins, few measurements have been made directly on the short-lived particles. There are thus five important quantities to be measured on each newly-discovered particle, and the object of this article is to describe how these measurements have been made and to explain the principles which are involved.

The two pieces of apparatus which have proved most helpful in studies of fundamental particles are the cloud chamber and the photographic emulsion. Each of them renders the path of any charged particle visible so that a picture of the particle's movements during the time it was in the detector may be obtained. In the cloud chamber, the track of the particle is marked by drops of condensed water vapour, while in an emulsion it is marked by silver grains which, when the emulsion is developed, appear as black dots on a clear background. Measurements made on the tracks seen in a cloud chamber or emulsion may, in favourable cases, yield information about the particle which produced the tracks.

Recently great interest has been aroused by measurements made on particles which decay in the detector. In cases of this type, measurements can be made on the secondary particles and, making use of the conservation laws, the nature of the parent particle can be inferred. This is of particular use where the parent particle is neutral, because it will not leave any track in the detector and direct measurements would be impossible. The physicist's stand-bys in these cases are the laws of conservation of energy, charge, linear momentum, and angular momentum.

In classical mechanics, energy and mass are each conserved in any interaction. In a simple case, suppose a body splits into

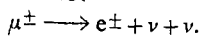
two parts. The total mass of the two parts will equal that of the original part and their total energies and momenta will also add up to those of the original body. It almost seems a matter of common sense! In the case of a fundamental particle decaying, the laws are slightly complicated because the laws of mass and energy are not individually true. A fundamental particle always decays into particles whose total mass is less than that of the parent particle. The mass which is 'lost' is converted into energy which is imparted to the decay products, causing them to fly apart. The total amount of energy-plus-mass is thus conserved although mass may be lost and energy gained. The most convenient unit of energy is the electron-volt (eV); that of momentum can be expressed as electron-volt/velocity of light (eV/c). For particles of high energy, momentum and energy are, in these units, nearly equal numerically.

The law of conservation of momentum has interesting consequences. Suppose a particle decays at rest into two other particles which move away from the scene of the decay with energy provided by the 'lost mass'. The tracks of the two decay products *must* lie in a straight line, because if they did not they would have a residual resultant momentum and the conservation law would be disobeyed. Similarly, if a particle decays at rest into three other particles, the tracks of the three decay products must lie in one plane. Where there are only two decay products, they must have a given total energy (equal to the lost mass) and yet their momenta must balance. There can be only one solution to this problem, and so if only two decay products are produced they must each have a unique energy.

The laws of conservation of charge and angular momenta are complicated by the existence of negative charges and spin. The total charge or spin after decay must equal that before decay. Thus a positive τ -meson which carries +1 unit of charge decays into three π -mesons each carrying a single unit of charge, but as one of the decay products is negatively-charged, the total charge of the decay products is $+1 + 1 - 1 = +1$ which is the same as that of the parent particle. The magnitude of the τ -meson's spin is not known, but spin of the π -meson is one unit, so it is possible

that the spin of the τ -meson is three units if all the decay products are spinning in the same direction; though it is more likely to be one unit, in which case one of the decay products would have to spin in the opposite direction to the others.

The assumption of the conservation laws has led to the postulation of a fundamental particle called the neutrino, which is a particle having zero rest-mass, and a half unit of spin. It was first introduced to provide spin and momentum balance in the cases where nuclei decayed radioactively with the emission of electrons. It has also been useful in reconciling the decay of π - and μ -mesons with the conservation laws. As an example, consider the decay of the μ -meson. The electron, which is the only visible product, can have any energy between zero and 55 MeV. This shows us that there must be at least two other decay products, since if there were only one the decay electron would always have the same energy. The maximum energy which the electron can take also shows that the combined mass of the neutral products is very small. The only known particle having these properties is the neutrino, and accordingly the decay scheme of the μ -meson is written as follows:



It might have been argued that an alternative to the two neutrinos would have been two photons (i.e. γ -rays). This possibility has been investigated experimentally by searching for electron pairs caused by the materialization of the γ -rays. None, however, have been found.

From the above discussion it should be clear that the decay scheme of a fundamental particle is of great interest, and that a knowledge of it often leads to a better understanding of the properties of the parent particle. To find out about the particles concerned in a reaction, measurements must be made on the tracks observed in the cloud chamber or nuclear emulsion in which the reaction took place. If suitable measurements are made, it is possible to determine the momentum, energy, velocity, and rest mass of the particles which caused the tracks.

A charged particle travelling through a medium may be likened to an iron cannon ball fired through a forest of mag-

netic trees with magnetic leaves. As the cannon ball passes near a tree it will attract the leaves and some of them may be broken off their parent tree so that the path of the cannon ball is marked by a trail of falling leaves. If the cannon ball passes particularly close to a tree, it will be attracted to the tree and be deflected from its course so that the path of the cannon ball will not be straight, but sinuous. If the cannon ball actually hits a tree, the tree will be split up into fragments.

All these effects happen when a charged fundamental particle is travelling through a medium containing atoms; their results can be seen in cloud chambers and emulsions. The trees are the atomic nuclei which are relatively heavy, while the leaves are the electrons which are travelling in orbits round the nuclei. A trail of free electrons is left in the path of the particle, which is not straight because the particle is 'scattered' by nuclei. Occasionally a particle registers a direct hit on a nucleus, causing it to disintegrate as discussed by P. E. Hodgson in *Science News* 33.

It is the trail of free electrons which render the path of a charged particle visible in a cloud chamber or photographic emulsion. In a cloud chamber, the electrons and the ionized atoms (atoms with one or more electrons missing) form centres on which water drops can condense when the chamber is expanded. The number of ions formed by the particle in its passage through the chamber can be determined by counting the water drops produced in track. In a photographic emulsion, the electrons, set free from their atomic orbits, form centres for the growth of grains of silver, which can be developed. The process is more complex than that which takes place in a cloud chamber, but the number of grains produced in a track is related to the number of ions produced by the particle in the emulsion.

Returning to the cannon-ball analogy, we can see that if the cannon ball is travelling very fast, it will hardly have time to affect the leaves or be deflected by the pull of the trees, and we must expect the trail of falling leaves to be sparse and the course of the cannon ball to be nearly straight. This is true of particles, and it is found that the ionization produced by a particle, and its degree of scattering, both depend greatly on the speed of the

particle. The act of ionization slows the particle down so that it eventually stops. The range of a particle in a given medium depends on the energy it had when it first entered the medium.

An examination of a track in a cloud chamber or photographic emulsion can sometimes tell us something about the particle which produced it. The research worker is like a detective examining footprints in the snow; he may be able to deduce, from the trail of footprints, how fast the person who made them was going and how much he weighed. The ionization produced by a particle is a function of its velocity, while its range is a function of its energy and its mass, and its scattering is a function of its energy. Measurements of any two of the three quantities, ionization, range, and scattering, enable one to deduce the mass of the particle which produced the track. A further measurement of importance in cloud chamber work is the bending of the path of a charged particle in a magnetic field. The radius of curvature of the path is proportional to the momentum of the particle, and may be used in conjunction with one of the other measurements mentioned above to yield mass values.

When measurements are to be made on tracks, the great difference between the cloud chamber and photographic emulsion becomes evident. The cloud chamber is generally speaking a large detector, and the tracks observed in it may be as much as 50 centimetres in length. The gas in the chamber is of very low density. Thus, while a particle entering a cloud chamber will take a relatively long time to traverse the chamber, it is not likely to stop in the chamber because there are so few atoms to retard it, and, for a similar reason, its scattering will be slight. On the other hand, when the cloud chamber is operated in a magnetic field, the long tracks make it possible to perform accurate curvature measurements.

The photographic emulsion has a density about a thousand times greater than that of the gas in a cloud chamber, so that particles traversing an emulsion will be scattered and slowed down noticeably. Emulsions are usually very small by comparison, and especially are thin, so that the tracks observed are seldom more than 1 centimetre in length and measurements must

be made with the aid of a high-powered microscope. The small size of an emulsion means that in spite of its great stopping power particles are still likely to escape before coming to rest in the emulsion and take a much shorter time to traverse it than a cloud chamber. Magnetic curvature measurements are not usually profitable because, in such a short distance, the change in the direction of the particle caused by magnetic curvature is often less than that due to scattering.

The different characteristics of the two detectors have led to two broadly different lines of research taken by their respective advocates. Cloud-chamber workers have concentrated on investigating lifetimes and decay schemes of the shorter-lived particles, especially the neutral ones, while emulsion workers have concentrated on finding the accurate masses and the decay schemes of the longer-lived mesons.

A particle travelling at half the speed of light will take about 7×10^{-11} second to travel one centimetre, so that a particle is unlikely to decay during its passage through a nuclear emulsion unless its lifetime is of this order. On the other hand the same particle will take about 3.5×10^{-9} second to traverse a 50-centimetre cloud chamber. The heavy mesons and hyperons have mean lifetimes of about 10^{-10} second so that their decays are commonly met in cloud chambers. On the other hand, particles such as π - and μ -mesons with lifetimes of 10^{-8} to 10^{-6} second will pass right through a normal cloud chamber before decaying, so that the only chance of observing the decay of such particles is by slowing them until they stop in the detector. As the density of a cloud-chamber gas is so small, it is difficult to slow particles sufficiently to stop them, and L-meson decays have been studied most by arranging for them to come to rest in nuclear emulsions. Recent developments have made cloud-chamber and emulsion techniques overlap in a most satisfactory way.

MASS MEASUREMENTS

The masses of the electron and proton have been known a long time. The mass of the electron was originally found by J. J.

Thomson, who used a piece of apparatus similar to the cathode ray tube in a television set. A stream of electrons was directed on to the screen and the beam could be deflected by an electric field and by a magnetic field. A measurement of the two deflections could be used to determine the specific charge (i.e. the ratio, charge/mass) of the electron. An independent measurement of the charge was made by R. A. Millikan and the results were combined to give the mass of the electron. Refinements of the technique have resulted in a greater accuracy, and the mass is found to be $(9.1085 \pm .0006) \times 10^{-28}$ gm.

A similar method was developed by Aston for measuring the masses of the proton and other atomic nuclei. A description of Aston's mass spectrograph was given in *Science News* 2. Recently the masses of the proton and neutron have been found very accurately from a measurement of the energies released in certain nuclear reactions. A recent review of the atomic constants quotes the mass of the proton with an estimated error of one part in 40,000. The accuracy of proton and electron masses enables them to be used as standards of comparison for other particles.

The masses of π - and μ -mesons were first determined from range and ionization measurements made on cosmic-ray mesons observed in cloud chambers and emulsions. When π -mesons were first produced artificially in the Berkeley accelerator, accurate mass measurements on the mesons produced were considered a vital part of the research programme. The π -mesons were produced by bombarding a target with fast protons; and mesons of a given momentum were selected by defining their trajectory in a known magnetic field (Figure 1). Slits were arranged in such positions that mesons which passed through them could enter a photographic plate. The slits lay on a circular path of known radius and so the momentum of a meson which would take up a path of the right radius in the field which was applied could be determined very accurately. The detector was a photographic plate which the π -mesons entered at a glancing angle so that they came to rest in the emulsion. When the plate was developed, the mean range of the mesons in emulsion

could be formed and compared with that of protons of known momentum. In this way, the mass of the π -meson was compared with that of the proton. In a later experiment, the π -meson was used as a standard of comparison for the μ -meson. The accurate mass values so obtained have been useful in determining the masses of heavier mesons.

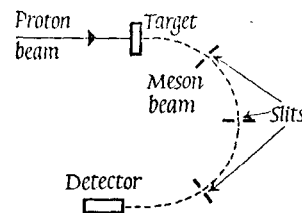


Fig. 1. Diagram to illustrate the production of π -mesons in the Berkeley accelerator.

When a heavy meson decays into known secondary particles, the sum of their energies and their masses is the mass of the parent particle. This fact has been used with great effect in determining the mass of the τ -meson, the θ -meson and the Δ^0 particle. Once the nature of the decay particles had been established, it was merely a question of finding a suitable event and measuring the energies of the decay particles. This method of finding masses has come into particular prominence since the use of stacked emulsions has become widespread.

An 'emulsion stack' consists of about twenty or more sheets of unsupported photographic emulsion, which are clamped together and exposed to the cosmic radiation usually on a balloon flight. After exposure, the emulsions are fixed to glass plates, and developed and inspected separately. If a meson decay is observed in one of the emulsions, the track of a secondary particle can be traced through from one emulsion to the next until its end is reached, or it leaves the last emulsion. In this way the disadvantage of the ordinary emulsion's thinness is overcome and the detector has the advantage of a fairly large size coupled with the stopping power of the ordinary emulsion.

Undoubtedly, the most accurate way of measuring the energy of a particle is from its range in a known absorber. Previously a number of heavy meson decays have been discovered in photographic emulsions and the masses of the primary particles estimated by adding the masses of the secondary particles to their energies as measured by ionization or scattering measurements. Now that stacked emulsions are in use, however, the secondary particles can be traced through from emulsion to emulsion, and there is a much greater probability of finding the ends of the tracks and measuring the ranges of the particles. This has resulted in greatly increased accuracy, so that for instance the mass of the Λ^0 particle has been found to one part in a thousand.

In an attempt to obtain stopping power when using a cloud chamber, Professor Leprince-Ringuet's group at Paris have developed a double cloud-chamber system. Two cloud chambers are placed one above the other; the upper chamber is in a powerful magnetic field while the lower chamber contains a series of metal plates. A charged particle which travels through the upper chamber takes up a curved path in the magnetic field and its momentum may be measured. If it comes to rest in one of the horizontal plates in the lower chamber, its range in the material of the plates is then known, and its energy may be deduced. From the combined measurements, the mass of the particle can be found fairly accurately. The results obtained so far are very interesting and may indicate the existence of yet another meson.

When it is required to measure the mass of a particle which does not come to rest in the detector, use must be made of ionization measurements combined with curvature measurements (in a cloud chamber) or scattering measurements (in a photographic emulsion). Ionization is measured in cloud chambers by counting the number of drops of water which condense to form the track of the ionizing particle. It is a tedious job though, and unless very special precautions are taken, does not yield accurate results. In an emulsion the number of developed silver grains in the track are counted and great accuracy is attainable. A typical track would have 300 grains per millimetre of track, so that the

error due to random fluctuations can be reduced to a few per cent by counting, say, 3 millimetres of track.

Errors due to uneven development are very much more serious, and it is usual to make measurements only on plates which have very low distortion and are evenly developed. Even then, careful calibration is necessary if results of grain counts are to be significant.

Curvature measurements are made on tracks recorded in photographs of the cloud chamber. An image of the track may be projected on to a screen through a special prism which can be adjusted to compensate the curvature of the track. The degree of adjustment required gives the curvature of the track. Alternatively the photograph is examined under a low-powered microscope and measurements of the coordinates of the track are made from which it is possible to calculate the curvature. In a well-adjusted cloud chamber measurements of momentum may be made on tracks with momenta as high as $2 \times 10^4 \text{ eV}/c$.

In photographic emulsions, scattering measurements may be made with great precision by plotting the coordinates of the track. The track is first aligned with the direction of the stage motion and then it is measured by moving it across the field of view in steps of say a millimetre and making successive measurements of the displacement in a direction at right angles to the direction of motion. If a straight line parallel to the motion were examined in this way, the displacement would not change; or if the line were inclined to the direction of motion the displacements would increase or decrease uniformly. Scattering of a track has the effect of causing variations of the displacements which can be determined from the second differences of the readings taken.

For tracks which are so energetic as to be very slightly scattered, the 'scattering' of the microscope stage motion must be taken into account. This effect is known as the 'noise-level' of the stage. Several microscopes have been produced recently in which the noise-level is greatly reduced by the use of kinematic stages of special design. Even so, some cosmic rays produce tracks so straight that no scattering can be observed. These

tracks caused by particles of tremendous energies are probably the closest approximations to a perfectly straight line which exist.

Measurements on tracks radiating from nuclear disintegrations by ionization-scattering methods have established that both light and heavy mesons are created in these miniature explosions. It is likely that the increasing use of emulsion stacks will permit more accurate measurements on the longer tracks available, and will lead to further discoveries. The main problem in this work is the great time and patience required to produce results. The measurements take a long time and require skilled personnel; even the labour of finding events to measure is crippling unless a large team of trained scanners is available.

LIFETIME MEASUREMENTS

The mean lifetimes of fundamental particles are very short, so that measuring the time before the particle decays is very difficult. Straightforward timing techniques are now capable of measuring times of the order of a few millimicroseconds (10^{-9} sec.), but even this is not short enough for some fundamental particles. Physicists have got over this difficulty in some cases by measuring the distances travelled by particles before they decay. In this case, while the time is very short, the particle is travelling so fast that it can cover a measurable distance before it decays.

The mean lifetime of π -mesons has been measured by allowing a beam of artificially-produced mesons to pass through three fixed counters and a fourth which could be moved (Figure 2). When the fourth counter is near to the other three, mesons passing through them are likely to pass through the fourth counter. As the scintillator is moved farther away, the mesons have more time in which to decay while travelling between the third and fourth counters, and the number of mesons detected decreases. From the rate of decrease with the distance between the third and fourth counter, the lifetime of the π -mesons could be found.

Recently, the mean lifetimes of π - and μ -mesons have been found simultaneously by allowing positive π -mesons to decay in

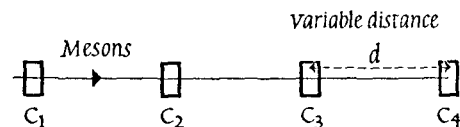


Fig. 2. Arrangement of counters (C_1 , C_2 , C_3 , C_4) used to determine the mean lifetime of π -mesons.

a large liquid scintillator. The passage of a charged particle in a scintillator produces a flash of light which is converted into an electrical impulse by means of a photomultiplier. With suitable liquids these pulses can be made very short so that accurate timing is possible. In the experiment, the pulses from the photomultiplier caused by the π -meson as it entered the scintillator produced a flash of light which was followed after a time equal to its lifetime by another due to the secondary μ -meson which in turn was followed by a third due to the μ -meson's decay electron. The average time between the first and second pulses gave the mean lifetime of the π -meson and that between the second and third pulses the mean lifetime of the μ -meson. Direct timings of such short intervals have only become possible during the past three years with the introduction of rapid-response photomultipliers and liquid scintillators.

The general technique of lifetime measurements in cloud chambers has been difficult because the interesting particles are so rare and so difficult to identify with certainty. The clarification of ideas which arose from the Bagnères conference has led to the establishment of the decay schemes of the Δ^0 particle and the θ -meson and analyses of these events observed in the Manchester University cloud chambers have been carried out.

The decay of a neutral particle in a cloud chamber is observed as a pair of tracks originating from the point where the parent particle decayed. The track of the parent particle is of course invisible, so that the event usually looks like an inverted V. For this reason the parent particles were often described as V-particles in the early literature. From the measured momenta of the decay products, the momentum and line-of-flight of the parent particle can be calculated if its nature is known. The momentum

and line-of-flight can be translated into the time between entering the chamber and decaying. In this way, a series of photographs of decays can be used to determine the mean lifetime of the particle. Two precautions must be taken in measurements of this sort. First, the time dilation due to the velocity of the particle must be taken into account. As already mentioned, the lifetime of a particle increases with its velocity, so that the proper lifetime of the particle must be calculated in each case before averaging the results. The second precaution concerns the finite size of the chamber. A particle will take a finite time to traverse the chamber, and so the particles which take longer than this time to decay will not be observed in the chamber. This means that lifetimes measured by the method outlined above will be shorter than the true value because of the long-lived examples which have escaped from the chamber and have therefore been omitted from the analysis. This effect can be allowed for theoretically if the distance that each of the particles could have travelled in the chamber, had it not decayed, is measured as well as the distance it did travel before decay.

The lifetime of the neutral π -meson has presented a difficult problem because it is so extremely short. Cases where a π^0 -meson has been emitted from a nuclear disintegration and has decayed directly into an electron pair and a γ -ray have been measured in nuclear emulsions. The distance between the centre of the disintegration and the start of the electron pair is usually very short (about 10 microns), so that observations of this sort are impossible in a cloud chamber and only just possible in an emulsion when the π^0 -meson emerges at great velocity so that the time dilation is noticeable.

One final measurement of great interest is that of the mean lifetime of the free neutron. The neutron decays according to the scheme $n \longrightarrow p + e + \bar{\nu}$. Robson working in Canada has counted the number of decay electrons in an intense beam of neutrons from a nuclear reactor pile. From a study of the variation of the number of electrons with the intensity of the neutron beam he has found the mean lifetime of neutrons.

When negatively-charged particles are brought to rest in matter, they may be attracted into the nucleus of an atom before they decay. When this happens, the nucleus becomes greatly excited and usually disintegrates. In Hodgson's article (in *Science News* 33) a photograph was shown of a negatively-charged π -meson which came to rest and was absorbed by a nitrogen nucleus. The effect of this alternative method of terminating the existence of a negatively-charged particle is that the mean lifetime is reduced. For π -mesons, the capture probability is so high that they hardly ever have time to decay. For μ -mesons the capture probability is lower, and may be found by measuring the way the lifetime is modified by the capture process. Work of this sort is likely to lead to interesting information on the structure of the nucleus.

The results of a great number of measurements have been summarized in the table of fundamental particles. It is almost certain that this table will be in some respects out of date in a year's time as further evidence is collected. It is to be hoped that a clearer picture of the fundamental particles will lead to a theoretical interpretation which will explain the present known facts and predict new phenomena with accuracy. In the meantime, experimental results are yielding facts of great interest and importance to physicists everywhere.

MESON THEORY OF NUCLEAR FORCES

G. FELDMAN

ONE of the most interesting chapters of physics has been man's discovery of the forces of nature. We are all familiar with the gravitational force which holds us down on the earth and which keeps the planets revolving in their orbits. A little less familiar is the electromagnetic force which manifests itself in the attraction of two unlike charges. The law of attraction is Coulomb's inverse square law. Early in the present century we became aware of a new force – the force inside an atomic nucleus. We discovered that the nucleus consisted of nucleons (neutrons and protons) bound tightly together. Electromagnetism could not account for this force since protons would repel rather than attract one another. It was also evident that gravitational forces were much too weak. Thus we had discovered the existence of a new force, the nuclear force. The progress that has been made in understanding the nature of these nuclear forces has been reported in earlier issues of *Science News*,* and some of the discussion in this article may be in part a repetition.

Of the three forces, gravitational, electromagnetic, and nuclear, it seems that the electromagnetic force is the one whose properties are best understood by physicists, and in order to discover the nature of nuclear forces we often use electromagnetism as an analogy.

It is interesting to look back for comparison to an earlier problem of physics, that of the relation between the nucleus as a whole and the electrons which surround it. This we may describe as atomic physics. The comparison is then between the

*Especially in *Science News* 2, and in articles by Professor R. E. Peierls in *SN*6, by T. Price in *SN*16, and by J. Little in *SN*23.

position of atomic physics before the discovery of quantum mechanics and the position of nuclear physics today.

At the beginning of the century we knew the force which held the atom together (simply the electromagnetic force), but we did not have the proper theory to explain the relative motion of the electrons and nucleus under the influence of this force. The invention of quantum theory (or more precisely the discovery of Schrodinger's equation and Dirac's equation) led to a very satisfactory explanation of this motion. The position in nuclear physics today is that we probably have the correct theory, and if we could solve the equations involved, we would know the force (or in other words the interaction) between nucleons. Thus it seems that the problem is simply one of mathematical complexity. Of course, it is possible that our present theory is wrong and that a new approach is needed, but more of this later.

THE INTRODUCTION OF MESONS

In trying to discover the nature of the interaction inside the nucleus, H. Yukawa, in 1935, used as an analogy the interaction inside the atom. As I have stated above, this latter interaction is purely electromagnetic. More precisely, we mean that two particles situated at a distance r from each other with charges of opposite sign attract according to the inverse square law of Coulomb (that is, the force of attraction is proportional to $1/r^2$). However, it is difficult to conceive of two particles separated by some distance affecting one another, and we like to think of this force or disturbance as being transmitted by some means. This we do by associating with each particle an entity called a field which pervades all space and whose behaviour is described mathematically by Maxwell's equations of the electromagnetic field. Quantum theory tells us that we may look upon this electromagnetic field, or radiation field, in terms of an equivalent picture involving photons. These photons or light quanta are the smallest units of radiation energy and behave in many ways like particles, except that they travel with the velocity of light and have zero mass. In terms of this photon picture we find that we may look upon the interaction between two

charged particles as pictured in Figure 1. Charged particle *a* emits a photon at *P*, which charged particle *b* absorbs at *Q*, or

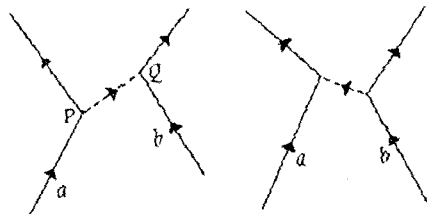


Fig. 1. Electron-electron or nucleon-nucleon interaction.

vice versa, and thus both *a* and *b* go off in different states of motion; that is, they have interacted. It is important to realize that the photon emitted is a 'virtual' photon. This means that a charged particle (e.g. an electron) moving freely cannot emit (or absorb) a photon without violating the firmly established laws of conservation of energy and momentum. Accordingly, this process of a single electron emitting a photon is unobservable and we call the photon virtual. This virtual photon has an existence in so far as the uncertainty principle allows the law of conservation of energy to be violated by an amount δE provided it is 'paid back' in a time δt where the product $\delta E \cdot \delta t$ is of the order of h (Planck's constant). In the process shown in Figure 1 we do not observe any photon but simply two charged particles which undergo a change in their states of motion.

It is this picture of the electromagnetic interaction which we use in order to try to explain the interaction between nucleons. There are also two experimental facts at our disposal: (1) the interaction between nucleons is much stronger (about 100 times stronger) than that between charged particles, and (2) the range of the nuclear interaction (that is, the distance over which the interaction is effective) is much shorter than the range of the electromagnetic interaction (1.5×10^{-13} centimetres compared to infinity). The meaning of range is clear: when two nucleons are within a distance of 1.5×10^{-13} centimetres, they attract each other with a considerable force, but

outside this distance they have no effect. Of course, the fact that protons are charged means that there always exists an electromagnetic repulsion between them, but inside the range 1.5×10^{-13} centimetres the nuclear attraction completely swamps the electromagnetic repulsion. Returning to Figure 1 we now think of *a* and *b* as two nucleons rather than two electrons. The particle emitted at *P* and absorbed at *Q*, which is analogous to the photon, is called a meson. The fact that the range of the interaction is finite implies that the meson has a non-zero mass. It is as if *a* and *b* are throwing balls to each other. If one set of balls is lighter than another set, the former will travel farther, or in other words the range of interaction should be inversely proportional to the mass of the particle emitted. For the range quoted above it turns out that the mass of the meson should be about 275 times the mass of an electron. Just as the photon emitted and absorbed in the electromagnetic interaction is virtual, so is the meson which takes part in the nuclear interaction. However, this does not exclude the possibility of observing real mesons (or real photons for that matter). Consider the process pictured in Figure 2. Nucleon *a* emits a meson at *P*, which nucleon *b* absorbs at *Q*; and then nucleon *a* emits another meson (1) at *R*. This latter meson (1) can be real since it is now possible to satisfy the laws of conservation of energy-momentum. That is, provided nucleons *a* and *b* have sufficient energy available to create the mass of a meson (from Einstein's relation, the energy needed is $E=mc^2$, where *m* is the meson mass and *c* is the velocity of light) these

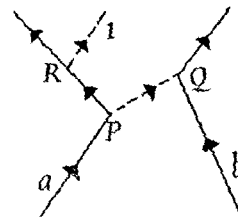


Fig. 2. Pion production: two nucleons (*a* and *b*) interact, and, if enough energy is available, a real meson (1) is formed.

two nucleons can turn into two nucleons plus a meson. What we observe is that two nucleons collide and coming out of the collision are two nucleons plus a meson. (These are not necessarily the same nucleons, because if a proton and neutron collide to produce a meson of positive charge, the two nucleons coming out must be neutrons in order to conserve charge.) It is just this process involving the collision of two nucleons which we use in order to produce mesons artificially in the laboratory. These mesons which we believe are responsible for nuclear forces are called π -mesons or pions. They were first discovered in cosmic rays in 1947 by G. P. S. Occhialini and C. F. Powell.

Pursuing this picture of Yukawa's still further we can see what other pion processes are possible. For example, the existence of multiple pion production in nucleon-nucleon collisions is possible. The meaning of this is that, rather than a single pion coming off as in Figure 2, there can be any number of pions produced, provided only that there is sufficient energy to produce the rest masses of the pions. Other possible processes are pion-nucleon collisions and 'photomeson production'. The latter process can be pictured as in Figure 3; a photon collides with a nucleon to produce a pion plus a nucleon. All of these processes have been confirmed experimentally in the laboratory since we

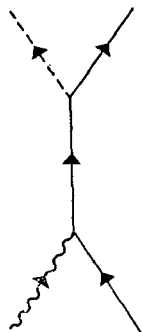


Fig. 3. Photo-meson production: a photon collides with a nucleon to produce a pion plus a nucleon.

now have machines in operation which can produce nucleons and photons of sufficiently high energy.

PROPERTIES OF PIONS

The simple picture of Yukawa's outlined above is not the whole story. It accounts qualitatively for the existence of pions and for reactions involving them. It also estimates the pion mass. But, in particular, it shows us that the interaction amongst nucleons is intimately connected with the interaction between nucleons and pions. Once we have discovered the latter interaction, we have discovered the former (provided only that we can solve the mathematical equations involved). Before we can begin to establish the detailed mathematical form of the pion-nucleon interaction we must determine experimentally certain properties of the pion. These are its mass, charge, spin, and 'intrinsic parity'. I shall attempt to define this last concept later. We know the values of these quantities for the photon. They are zero mass, zero charge, spin one, and positive parity. The fact that the photon has spin one is just another way of saying that the specification of the electric and magnetic fields associated with a charged particle involves direction as well as magnitude; that they are vectors rather than scalars. In the present state of theories these properties of pions are the minimum we need in order to explain what will happen when they interact with other forms of matter. One may hope that in the not too distant future some more extensive theory will be produced which will explain not only the effects of interaction but also these properties of the fundamental particles.

The mass of the pion is 273 electron masses. This can be determined in many ways, one being to measure the pion momentum and total energy when a pion passes through a cloud chamber which is placed in a strong magnetic field. We then use a form of Einstein's relation which is equivalent to $E=mc^2$ but is expressed in terms of the total energy, momentum, and rest mass of the pion.

The pion exists in three charge states. That is, the charge of a pion is either positive, negative, or neutral. At first only the

positive and negative pions were found, but later on the neutral one was found also. The neutral pion was suspected to exist because of the reasonably well confirmed experimental fact that nuclear forces are 'charge independent'. Charge independence means that the neutron-neutron, proton-proton, and neutron-proton forces are the same when these pairs of particles are in the same state of motion. This is true, of course, only after we have subtracted out the specifically electromagnetic force that exists between proton and proton. To see why this fact of charge independence implies the existence of a neutral pion we resort again to some simple pictures as shown in Figure 4. The picture for the neutron-proton force would be either Figure 4(a) or 4(b).

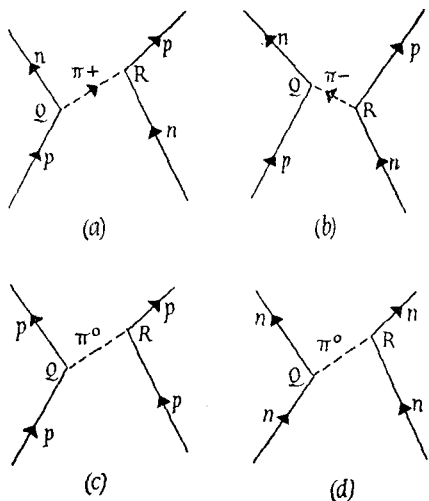


Fig. 4. (a) and (b), neutron-proton interactions; (c), proton-proton interaction; (d) neutron-neutron interaction.

In Figure 4(a) a proton p emits a positive pion, π^+ , at Q and changes into a neutron n . The π^+ is then absorbed at R by n which changes into a proton p . In Figure 4(b) a negative pion is

exchanged. However, in order to explain the proton-proton or neutron-neutron force by means of a similar picture it is necessary to assume that a neutral pion, π^0 , is exchanged, because if either a π^+ or π^- were exchanged we could not conserve charge at either Q or R . The conservation of charge is one of the most firmly established laws of nature. Thus, it seemed that from a strictly theoretical point of view neutral pions should exist. Just how to include them in the theory was shown by N. Kemmer.

The spin of the pion is zero, and this was found by making use of a principle of statistical mechanics called 'the principle of detailed balance'. Two similar experiments were performed by J. Steinberger, W. F. Cartwright, and others which we may symbolize by

- (1) $p + p \rightarrow \pi^+ + d$
- (2) $\pi^+ + d \rightarrow p + p$

where p is a proton, d a deuteron (a proton plus a neutron bound together) and π^+ a positive pion. The principle of detailed balance states that the probabilities for the processes (1) and (2) are the same at any given total energy. Entering into the result for the number of events of type (2) is the factor $2s+1$ where s is the spin of the pion. The experiments were done sufficiently accurately to determine that s is zero.

I shall now try to explain the concept of 'intrinsic parity', which thus far has been mentioned only by name as a property of the pion which must be experimentally determined. It may be useful at this point to recall that physical quantities are conveniently distinguished according to whether their specification does or does not involve direction. Energy, for example, is independent of direction, and a quantity of this kind is described as a 'scalar'. The momentum of a moving object, on the other hand, involves direction as well as magnitude, and a quantity of this kind is described as a 'vector'. However, there exist other quantities (not observable physically although combinations of them may be) which are neither scalars nor vectors, and to describe them we must introduce a new concept called 'intrinsic parity'.

In a more sophisticated way we may suppose that we have an

entity which is expressed in terms of the usual three spatial coordinates x, y, z . If the entity is a scalar – energy in the above example – it is unaffected by any change in the coordinate axes, and hence by the change known as 'reflection' in which x, y, z are changed into $-x, -y, -z$. However, there exists another entity called a 'pseudoscalar' which, like a scalar, is unaffected by all other changes of coordinate axes. But when the coordinate change is a reflection, it changes sign keeping its numerical value the same. A scalar (changed in neither sign nor numerical value) is said to have 'positive intrinsic parity'; a pseudoscalar (changed in sign but not in numerical value) is said to have 'negative intrinsic parity'.

Associated with each fundamental particle (e.g. neutron, proton, electron, pion, etc.) is a mathematical entity called a 'wave amplitude' or 'wave function'. This amplitude, say ϕ , depends on the three spatial coordinates. The total energy of a system of particles is a scalar, as we have seen. However, this does not imply that our wave function ϕ must be a scalar. It turns out that provided ϕ is always multiplied by some other amplitude, the product behaving as a scalar, ϕ , may be either a scalar or a pseudoscalar; that is, it may have either positive or negative intrinsic parity.

I have somewhat simplified the situation by implicitly assuming that all wave amplitudes are scalars or pseudoscalars. This is true for particles of spin zero. If a particle has spin one, the wave amplitude is a vector Φ ; and there are two kinds of vectors, polar vectors and pseudo (or axial) vectors which do or do not change sign respectively on reflecting the coordinate axes in the way mentioned. Those familiar with classical electromagnetic theory will recall that the electric field is a polar vector and the magnetic field a pseudovector. (A polar vector, e.g. force or velocity, is represented by a straight line with an arrow on it, and a pseudovector, e.g. circulation, simply by a line.) W. K. H. Panofsky has discovered by means of an experiment, which I shall not describe here, that the pion has negative parity. Since we also know that the pion has zero spin, the pion wave amplitude is thus a pseudoscalar.

THE PION-NUCLEON INTERACTION

Having established all of the intrinsic properties of the pion (and since we know them also for the nucleon) we shall attempt to discover the nature of the pion-nucleon interaction. Once again, we turn to electromagnetic theory for a clue. However, we do not turn to classical (i.e. non-quantum mechanical) electromagnetic theory described either by Maxwell's equations or by the laws of Coulomb, Faraday, Oersted, etc., but we look to the quantum electromagnetic theory called 'quantum electrodynamics'. This latter is the theory of systems of electrons (both positive and negative) and photons, and it is also consistent with Einstein's theory of special relativity. Quantum electrodynamics had been in existence almost since the birth of quantum mechanics; however, it always gave rise to certain infinite quantities which could not be readily interpreted. Soon after the war, in about 1948, the theoretical physicists, F. J. Dyson, R. P. Feynman, J. Schwinger, and S. I. Tomonaga developed a procedure called 'Renormalization' (a mathematical procedure with a physical basis) which effectively resolved the difficulty over the infinities. In fact, we can now predict to almost any degree of accuracy the results of experiments on processes which are entirely electromagnetic in nature. One of the most accurate tests at present is certain extremely small splittings of hydrogen spectral lines called the Lamb-Retherford shift.

The complete success of modern quantum electrodynamics has greatly encouraged the attempt to construct the theory of pions and nucleons which we call 'meson field theory'. I shall go into some detail as to the types of theory possible, making use of our knowledge of the properties of pions. Appearing in the photon-electron interaction of quantum electrodynamics is the wave amplitude of the photon. This function is a polar vector since the photon has spin one and positive intrinsic parity. (As stated above, this is implicitly connected with the fact that the electric and magnetic fields are vectors.) The photon amplitude is multiplied by a known quantity which makes the expression for the total energy of the photon-electron system a scalar. When

we come to meson field theory we use the fact that the pion is a pseudoscalar. It turns out that the pion wave amplitude (appearing in the total energy expression) can be multiplied by two possible quantities. Both of these quantities contain the nucleon wave amplitude and in the jargon of field theory we say that the pion is 'coupled' to the nucleon. This term which arises from the 'coupling' is called the pion-nucleon interaction term. The two possible methods of coupling are called pseudoscalar and pseudovector. (They are analogous to the cases of a particle having either an intrinsic charge or an intrinsic dipole moment.)

The procedure of renormalization has been extended to meson field theory by P. T. Matthews and A. Salam. They find that the pseudoscalar coupling theory can be renormalized, but that the pseudovector theory cannot. In other words, we know how to handle pseudoscalar coupling, but not pseudovector coupling. Accordingly, we assume that the pion-nucleon coupling is indeed pseudoscalar.

By this process of reasoning and analogy we have deduced the form of the interaction between pions and nucleons. We might think that all that was now necessary was to proceed along the same lines as in electrodynamics to solve any problems involving pions and nucleons. Unfortunately, this is not the case. In electrodynamics the constant multiplying the photon-electron interaction term is e the charge of an electron. In the theory it is called the photon-electron coupling constant. We find it useful to introduce a dimensionless quantity α , known as the fine structure constant. $\alpha = 2\pi e^2/hc = 1/137$, where h is Planck's constant and c is the velocity of light. The fact that α has this comparatively small numerical value is practically helpful, since we can solve the equations of electrodynamics only as a series of terms each containing a higher power of α ; i.e. as a power series in α . Thus each term is about 137 times smaller than the previous one, and so by the time we have calculated, say, three terms, the next term will contribute only a negligible amount. In meson theory, on the other hand, this helpful situation does not exist. The quantity analogous to the photon-electron coupling constant e is the pion-nucleon coupling constant g ; and the dimensionless

quantity, analogous to the fine structure constant, is $2\pi g^2/hc$. The numerical value of this constant, instead of being a small fraction, lies between 1 and 40. Physically, this implies that nuclear forces are about 100 times stronger than atomic forces. Mathematically, it implies that any attempt to solve the equations of meson theory as a power series in this constant is quite hopeless. It is indeed probable that successive terms get larger rather than smaller as the series proceeds. We may sum up the situation in meson field theory today by saying that we have a set of complicated equations which we must solve by some means that does not involve a series expansion in $2\pi g^2/hc$.

SOME RECENT EXPERIMENTAL RESULTS

Originally we had set out to explain the forces between nucleons. We discovered that this can be explained (in principle at least) in terms of the interaction between pions and nucleons. The equations involving the interaction between a pion and a nucleon are perhaps easier (but not much) to solve than those for nucleon-nucleon interactions, and so theorists look forward to experiments performed on pion-nucleon collisions. Of course, experiments on nucleon-nucleon collisions and pion production resulting from such collisions are also of immense interest. With the new proton synchrotrons (*Science News* 22 and 26) in operation at Berkeley and Brookhaven in the United States and at Birmingham in England we can now reach proton energies up to about 5 BeV (five thousand million electron volts) and pion energies up to about 4 BeV. Already considerable data have been accumulated on pion-proton collision experiments for pion kinetic energies from 0 to 1.5 BeV. The curves for the cross-sections (effectively probabilities) of pion-proton collisions exhibit one and possibly two 'resonances'. (These resonances are simply peaks in the curves.) This implies the existence, in some sense, of an excited nucleon which may be doubly charged. Such an excited state is consistent with other experiments done at Brookhaven on single and double pion production in nucleon-nucleon collisions. The experimental results

keep flowing in and they all must be explained when the theoretician solves the equations of meson field theory.

CONCLUSIONS

Even if the experimental results of pion physics could be satisfactorily explained there remain many other problems. One of the most important is the problem of explaining the existence and behaviour of the many new particles (e.g. the Δ 's, τ 's, and θ 's) found first in cosmic rays and now produced artificially. (See P. E. Hodgson's article in *Science News* 31 for an excellent survey of their properties, and that by R. M. Tennent in this number for methods of measurement.) Thus we see that a whole new vista is opening up and a much broader theory is needed to account not only for the pion-nucleon system but for all the other systems of particles.

As far as the pion-nucleon system alone is concerned, there are, at present, two schools of thought. One says that it is impossible to explain the results of pion-nucleon experiments without first broadening the theory to include, somehow, the new cosmic ray particles. The other school says that it is certainly necessary to have a much wider theory in order to explain all the facts known at present. Nevertheless, as far as the pion-nucleon results alone are concerned, the present theory, as outlined in this article, is a good enough approximation to the true theory and we must try to solve the existing equations. Whoever is right we shall perhaps know in the near future, for physicists the world over are relentlessly probing the workings of the most fundamental processes of nature.

POLAROGRAPHY

D. J. FERRETT

A WELL-KNOWN and perhaps apocryphal story attributes to the Chinese a method of torture in which drops of water fall constantly on to the forehead of the victim; and many Western ears must have been irritated by the periodic noise from a leaking tap. It is not only the period of such drops that is constant, however; their size and rate of growth do not vary, and each new drop has as clean and new a surface as its predecessor. A leaking mercury tap would be an eccentric addition to any home, but such a device is used by many analysts today. Mercury is used in this manner because, having metallic conductivity, it can be used as an electrode in an electrolytic cell in which a difference of potential is maintained across a solution of a salt (the electrolyte). Moreover, its ability to form liquid alloys (amalgams) with other metals enables the drop-like character of the electrode to be maintained even after electro-deposition of metals from solutions. All these properties – regularity of drop formation, the periodic establishment of a clean surface, metallic conduction, and the formation of liquid alloys – are of importance in the formation of the unique type of electrode used in polarography, the dropping mercury electrode.

Polarography, first discovered and explained by the Czech worker Heyrovsky in 1922, is one of the most versatile of all analytical techniques. Its uses include the analysis of small quantities of metals and the determination of the amount of cystine in a single hair. Its growing importance is shown by the 3,000 papers that have been published on the method; more than half of these have been published in the last ten years, while the present rate of publication is over 250 papers a year. But it may still be asked, why should any such a wide interest be taken in

polarography? Are there not conventional methods which suffice?

The answer to these questions is partly a general one. The fact that analytical chemistry is essential to all scientific investigation is often forgotten by many people to whom 'analysis' means the determination of a single known substance, or the spotting of one that is unknown and not too difficult, with the labels on the bottles taken for granted. The elaborate equipment and exact techniques of measurement used in many branches of science are useless if the composition and purity of the materials being examined are uncertain, and any explanation of the reactions that may occur must be preceded by a complete analysis of the products formed at all stages of these reactions. The second part of the answer is that polarography is a quick and sensitive method of analysis, which needs only small quantities of materials.

The dropping mercury electrode, which is the basis of the method, consists (Figure 1) of a thin glass capillary (0.03 to 0.05 millimetres in diameter) attached to a reservoir of mercury. From the tip of the capillary, drops of mercury issue, grow, and fall at the rate of one every three to six seconds. These drops are made the cathode of an electrolytic cell, the anode being a large pool of mercury into which the drops fall.

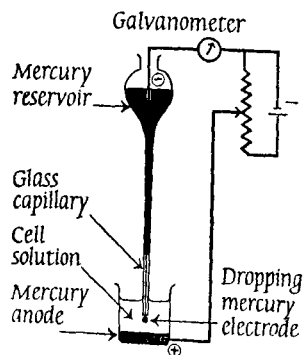
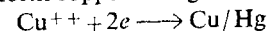


Fig. 1. The dropping mercury electrode.

When this cathode is immersed in a dilute solution of a metal ion, e.g. a solution of 6 milligrammes of copper chloride in a litre of water, and its potential adjusted to -1.0 volt, copper ions are 'reduced' to copper metal at the cathode, and dissolve in the mercury to form copper amalgam: i.e.



The reaction occurs only above a certain potential; this, the 'reduction potential', is a measure of the energy required to neutralize the charge on the ion.

The amalgam formed is sufficiently dilute to be liquid and is, therefore, removed from the electrode surface as the drop falls. The new drop as a consequence has a fresh mercury surface and, if the height of the mercury in the reservoir is constant, has the same size and shape as the previous drop. A succession of identical drops therefore falls from the capillary, producing a cathode whose surface is completely reproducible. This is in complete contrast, of course, to the behaviour of any solid metal electrode, where the initial deposition of copper would affect the shape and properties of the cathode.

The copper ions in the solution behave exactly as they do in any type of electrolytic cell, moving to the cathode under the electrostatic attraction between their positive charge and the negatively charged cathode. Their neutralization at the cathode causes a decrease in the concentration of the ions there, and a gradient is formed, therefore, between this depleted concentration and the unchanged concentration of the bulk of the solution. This concentration gradient is an additional factor causing the ions to move towards the cathode.

In polarography, conditions are established under which the movement of ions towards the cathode is governed by this second factor alone. In order to nullify the effect of the potential gradient, an excess of an 'indifferent electrolyte' is added to the solution. This indifferent electrolyte consists of a salt, e.g. potassium chloride, which is not reduced at the potential applied to the cell. The action of these indifferent ions in removing the attractive force on the metal ion reduced may be explained by assuming that the indifferent ions move to the electrode

under the influence of the potential gradient and accumulate there until the total potential produced by their interaction is equal and opposite to that applied to the cell. Under these conditions the copper ions diffuse to the electrode only under the influence of a concentration gradient. The concentration of indifferent electrolyte is generally at least a hundred times greater than that of the metal ion being reduced, being of the order of 0.1 gramme molecular weight per litre (0.1M).

If we consider the effect of slowly increasing the potential applied to such a system, we can see that, at potentials below the reduction potential of the copper ion, no current flows (see Figure 2). As the potential of the cathode is made more negative, reduction of the ions begins, and other ions will diffuse towards the cathode to replace those which have been reduced. On still further increasing the potential, both the current and the rate of diffusion of copper ions towards the cathode increase. This cannot continue indefinitely, however, and eventually a potential is reached at which all the ions arriving at the cathode are reduced. The effective concentration of these ions at this electrode is then zero, and the rate of diffusion of ions is a maximum. Further increases in potential have no effect upon the current, which is known therefore as the limiting or diffusion current, i_d , and the current-voltage relationship described can be represented as in Figure 2.

For any point on the graph we can write:

$$i = k_1 N \quad (\text{Eqn 1})$$

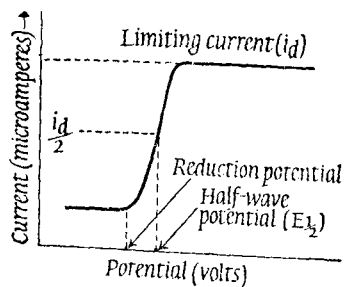


Fig. 2. Idealized current-voltage curve.

where i is the current and N is a measure of the number of ions diffusing to the cathode. And also:

$$N = k_2(C_s - C_s^0)/d \quad (\text{Eqn 2})$$

where C_s is the concentration of reducible ions in the bulk of solution, C_s^0 is their concentration at the electrode surface, and d the thickness of the layer through which the ions diffuse.

When all the ions reaching the electrode are reduced, $C_s^0 = 0$ and $i_d = kC_s$. The limiting current is therefore proportional to the concentration of reducible metal ion. This is the basic condition for all *quantitative* polarographic analysis.

The limiting currents normally obtained in polarography vary between 0.1 and 100 microamperes. These currents correspond to the reduction of only a very small proportion of the reducible metal ion in solution. It can thus be seen that polarography has the additional advantage of leaving the solution practically unchanged after analysis. Information of a qualitative nature can also be obtained from these current-voltage graphs, because the value of potential ($E_{1/2}$ in Figure 2), where the current is one-half of the limiting current, is unique, depending only on the particular ion being reduced; it is independent of concentration, cathode area, time between drops, etc. This potential is known as the 'half-wave potential' ($E_{1/2}$). Because it is unique, the ions which give rise to it can be identified, subject to the accuracy of measurement attainable.

THE INTERPRETATION OF POLAROGRAMS

Current-voltage traces, or 'polarograms', as in Figure 2, are normally obtained automatically, the potential applied to the cell being slowly increased by a motor-driven potentiometer and the current being recorded photographically or by a pen-recorder. A typical polarogram obtained in this way, for a solution of cadmium ions in 0.1M potassium chloride solution, is shown in Inset 11. It will be seen that this differs in two ways from the ideal form discussed above:

(1) The polarogram is not steady, but shows periodic fluctuations in current. These are due to the growth and fall of the mercury drops, for the limiting current is proportional not only to

the concentration of the solution but also to the area of the electrode. The current does not decrease to zero when the drop falls, however, for the type of galvanometer normally used to record the current does not respond rapidly enough to the current changes, and the polarogram shown is therefore obtained. This is very nearly the true average current.

(2) The base-line is not constant in value but increases steadily. This slowly increasing current is known as the residual current, and is due to the reduction of very small quantities of impurities and also to the fact that the interface between the mercury drop and the solution behaves as a condenser. The mercury drop, because of its negative charge, is surrounded by a layer of positively charged ions; this double-layer of charges acts as a condenser. A growth in the size of the drop will cause an increase in the area of the double-layer and will be accompanied therefore by a 'charging current'. Hence, in order to know the limiting current accurately, it is necessary to subtract the value of the residual current. This is normally estimated by extrapolation as shown in Figure 3. The existence of this residual current restricts the sensitivity of the polarographic technique, for when it is equal to or greater than the diffusion current, it is difficult to estimate the extrapolation accurately. As the residual current is about 0.5 microampere at -0.5 volt—i.e. equivalent to the diffusion current from a solution of $10^{-4}M$ metal ions, it is possible to measure concentrations of these ions of 10^{-2} to $10^{-4}M$ with an accuracy of ± 2 per cent, while concentrations of 10^{-4} to $10^{-5}M$ can be measured to ± 5 per cent.

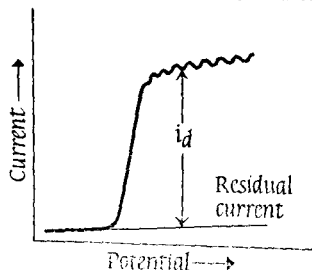


Fig. 3. To show the method of correction for residual current.

As the potential at which hydrogen ions are reduced at the dropping mercury electrode is approached and reached, the residual current begins to increase more rapidly. This factor becomes significant in neutral solutions at potentials more negative than -1.6 volts, although in alkaline solutions it is possible to work at even higher potentials. In regions of more positive potential, however, the dropping mercury electrode cannot be used above $+0.1$ volt, for at these potentials dissolution of the mercury begins to take place



Because the half-wave potential is a characteristic of the ion-species present in solution, it is possible to identify metal ions by this method. This is the basis of *qualitative* polarographic analysis. Values of half-wave potentials for some metals are given in Table I.

TABLE I: *Half-wave Potentials of some Metals (volts)*

copper	+0.02	zinc	-1.01
lead	-0.40	nickel	-1.09
thallium	-0.46	cobalt	-1.20
cadmium	-0.59	manganese	-1.50

These values follow the normal electrochemical series of the elements and, provided that the half-wave potentials of two metal ions in a particular solution differ by more than 0.20 volt, the waves due to the reduction of these ions are clearly separated and both metal ions can be estimated. Inset 12 shows a polarogram for a mixture of copper, lead, cadmium, and zinc ions in $0.1M$ potassium chloride solution. All four steps are clearly separated and can be easily measured.

Maxima

The interpretation of polarograms is sometimes made difficult by the appearance of maxima. These occur generally in the form of sharp peaks at the beginning of the appearance of the limiting current. This effect is illustrated in Inset 13, for a solution of copper in $0.1M$ potassium chloride solution. These maxima are perfectly reproducible phenomena whose origin is

still the subject of controversy. Heyrovsky attributes their occurrence to absorption of the reducible ion on the mercury drop. This increases the concentration of this ion at the electrode surface above that in the bulk of the solution. Other workers, however, have shown that maxima are associated with rapid movement of the solution around the mercury drop. Such movement would also cause an increase in the concentration of the ion at the electrode surface.

Although the occurrence of these maxima makes the measurement of limiting currents and half-wave potentials difficult or impossible, they can readily be eliminated by the addition of small quantities of surface-active materials (e.g. detergents) to the solution. These 'maximum-suppressors' are presumably absorbed at the mercury-solution interface. Some of these are highly specific in their action, but a solution of 0.005 per cent gelatin has been found to eliminate all types of maxima, and this substance is widely used in polarography.

THE USE OF POLAROGRAPHY IN ANALYTICAL CHEMISTRY

Although polarography has been applied to many chemical investigations, it has been most extensively used as an analytical tool. The sensitivity of the method and the ease and simplicity of operation make it especially valuable for the rapid analysis of small quantities of material.

The Determination of Oxygen

Oxygen is readily reduced at the dropping mercury electrode and produces two waves of equal height. The height of the first wave is directly proportional to the concentration of dissolved oxygen in solution. This is one of the most satisfactory methods for the determination of such dissolved oxygen. This type of polarographic determination has been extensively used in biochemistry for the study of such processes as the photosynthesis and respiration of green algae,* and for the determination of the

**Science News* 20 (1951), 'Photosynthesis'; *Science News* 32 (1954), 'Mass Culture of Chlorella'.

oxygen content of blood plasma and lymph. In the latter example, the oxygen content of samples as small as 1 millilitre has been successfully determined.

As the half-wave potential for the first oxygen wave is at -0.1 volt, and the concentration of oxygen in most aqueous solutions is about $10^{-4} M$, it is necessary to remove dissolved oxygen from solution before other substances can be estimated. This can be readily carried out by bubbling nitrogen or hydrogen through the solution, or, if the solution is alkaline, by the addition of a few drops of saturated sodium sulphite solution.

Metal Alloy Analysis

Mixtures of metal ions that are present in roughly equal quantities may, as we have seen, be estimated, if their half-wave potentials are separated by 0.2 volt or more. The lack of a sufficient separation need not, however, be accepted as final. The half-wave potential of an ion can be altered by changing its charge, or by adding to the solution a reagent, e.g. ammonia or a cyanide, which forms a complex compound with the ion*; so that, even if two metals are inseparable under one set of conditions, they may often be estimated under another. The data given in Table I refer to hydrated ions.

Many elegant methods exist that use such techniques. For example, in the determination of the lead and copper contents of steels the wave for the reduction of ferric iron (Fe^{+++}) precedes, and is very much larger than, those due to the small amounts of copper and lead present. These elements cannot therefore be determined polarographically, unless the iron is first reduced to the ferrous (Fe^{++}) state. The ferrous wave occurs at a more negative potential than those due to the copper and lead, and these two elements may therefore both be determined.

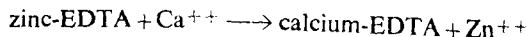
The determination of lead and nickel in brasses is similarly impossible in chloride solution, both because of the large wave due to the reduction of the copper and because the nickel and zinc waves coalesce in this medium. If the solution is made alka-

*See, for example, 'Shape of Inorganic Molecules' by R. S. Nyholm in *Science News* 20 (1951).

line, however, and cyanide ions added, the copper and zinc are both so strongly complexed that no reduction waves occur in the range studied, and the lead and nickel may be determined.

The polarographic technique is not necessarily limited to the determination of those ions that are reduced at the dropping mercury electrode. Thus, although aluminium has so high a half-wave potential that its waves cannot readily be measured, H. H. Willard and J. A. Dean, at the University of Michigan, found that the wave due to the reduction of an organic dye Solochrome Violet RS is split into two waves by the addition of aluminium ions to the solution. The height of the second wave is directly proportional to the aluminium concentration and has been used as a method for the determination of aluminium. A further ingenious use of this system has also been made, for it was discovered that small quantities of fluoride ions decrease the height of the second wave. G. F. Reynolds has shown that this decrease is quantitative and that fluoride ions can be determined in this way.

The same difficulty arises with calcium as with aluminium. It has been overcome lately by R. Pribil and Z. Roubal, who have devised a polarographic method for the determination of calcium in urine and blood. In this method, the complex compound formed between zinc and ethylene diamine tetra-acetic acid (EDTA) is added to the sample being analysed for calcium. The zinc-EDTA complex, like the zinc-cyanide complex, is so stable that the zinc in this compound is not reduced at the dropping mercury electrode. In the presence of the blood or urine sample the reaction



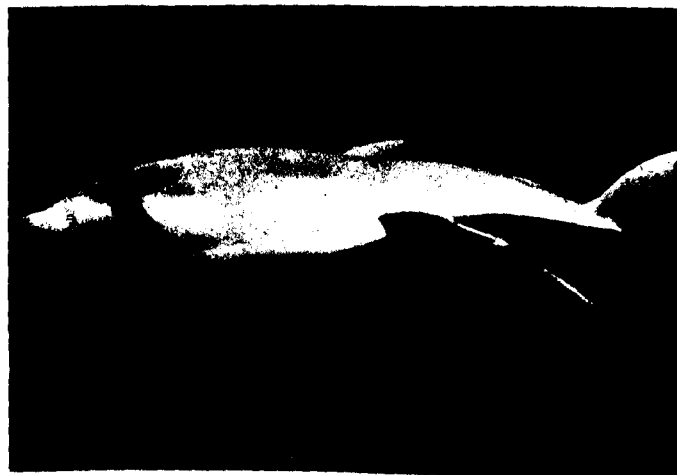
occurs, for the calcium-EDTA complex is more stable than the zinc-EDTA complex. Zinc ions are liberated, and these will be reduced at the cathode. The current that flows will therefore be directly proportional to the calcium concentration in the sample.

POLAROGRAPHY AS AN INDICATOR

Polarography can be used also as an adjunct to the classical method of volumetric analysis, in which one measures the



1. Photograph of a new-born Common Seal showing the main external features and the cylindrical form of the body.



2. Under-water photograph of female Bottlenose Dolphin (*Tursiops truncatus*) and suckling calf. (By courtesy of Marine Studios, Marine-land, Florida.)

3. Photograph of the renal stellate plexus of veins on the surface of the kidney and divided inferior vena cava of a young seal. See also Inset 5, which shows a cast of the vascular system; Inset 7 shows the inferior vena cava in a foetal Finner Whale. $\times 1/3$.



4. Photomicrograph of a section of a seal embryo showing the sphincter (a dark ring) developing about the inferior vena cava just above the diaphragm at the bottom of the picture. $\times 6$.





5. Photograph of a cast of the abdominal arteries and veins (black) of a young seal. There can be seen, *top*, the hepatic (liver) sinus; *lower right*, the renal stellate plexus shown from the outside in Inset 3; and, *centre*, the divided inferior vena cava. - 1,4.



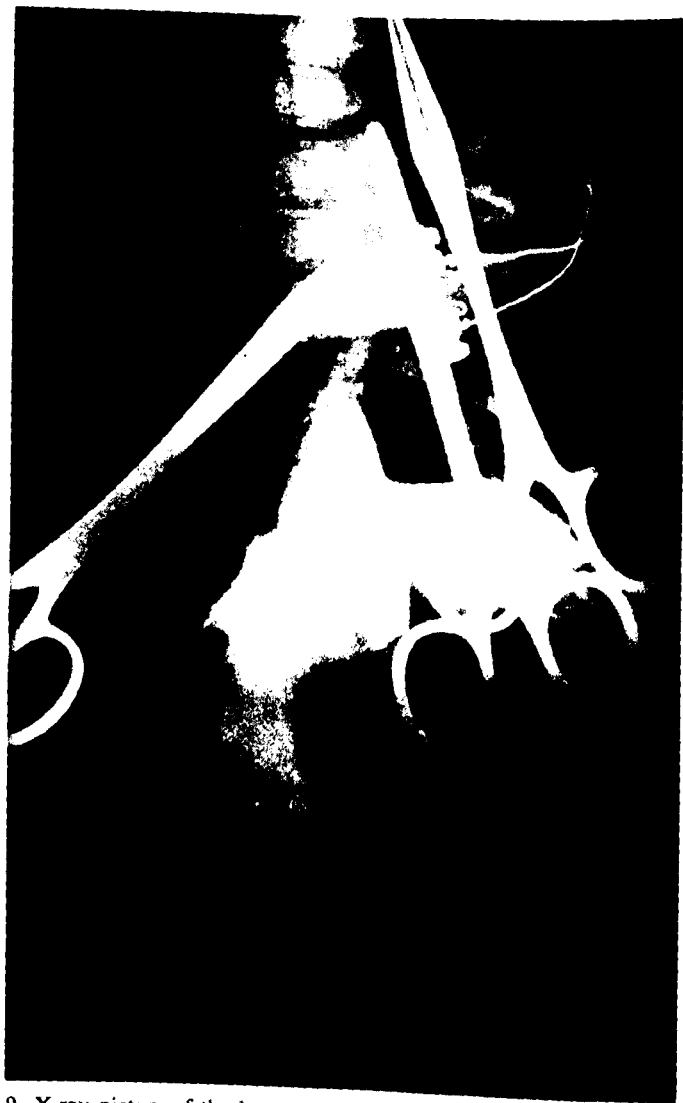
6. Photograph on a larger scale of part of the same cast as Inset 3, showing the multiple structure of the kidney. Note the cup-shaped receptacles (calyces) into which the many small units of the kidneys drain by separate openings. Nearly life size.



7. Photograph of the kidneys and divided inferior vena cava of a 92-cm foetal Finner Whale. $\times 1/2$.



8. Photograph of the extradural spinal vein of a 32-cm foetal Dolphin. The spinal cord has been removed and the photograph taken from the back. $\times 4$.

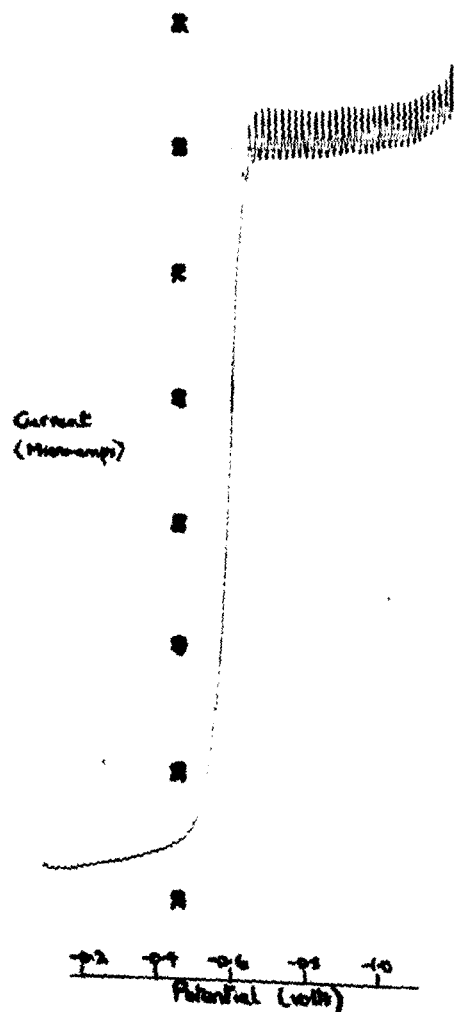


9. X-ray picture of the hepatic sinus and thoracic inferior vena cava outlined after injection of radio-opaque material into one of the right renal veins of a seal pup. $\times 1/2$.

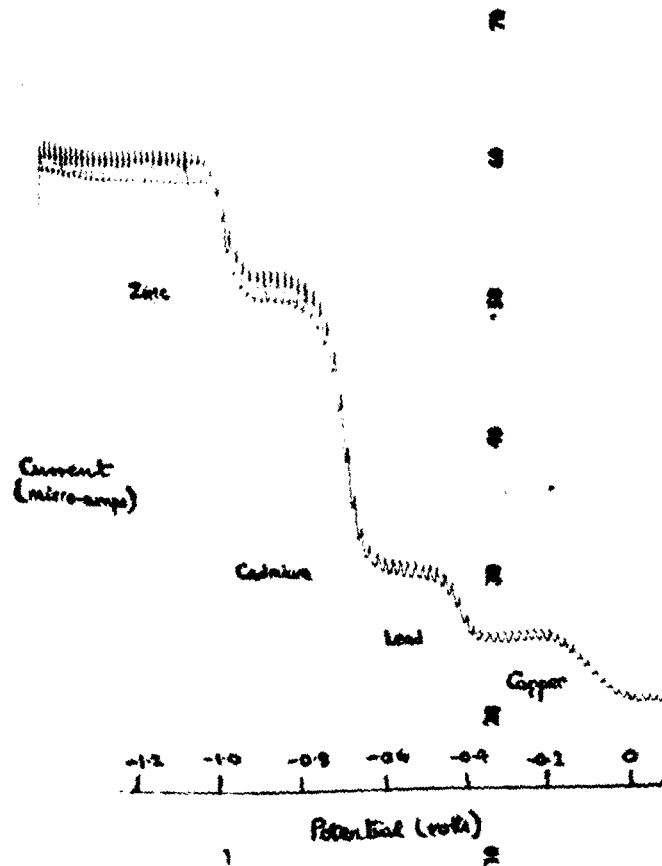


10. The same seal after stimulation of the right phrenic nerve and contraction of the sphincter.

POLAROGRAPHY

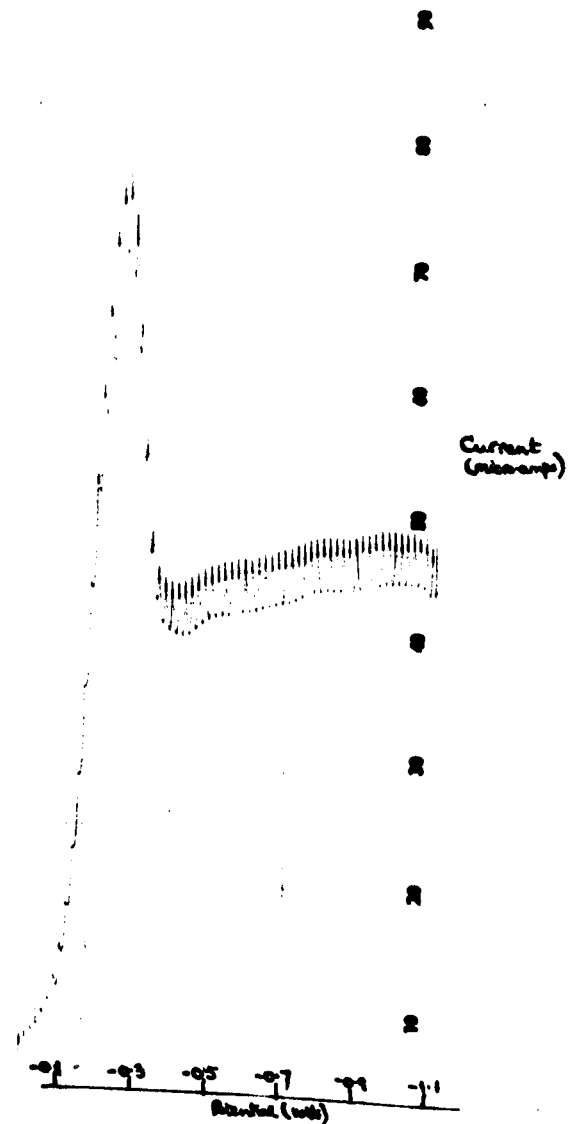


11. Polarogram for solution of cadmium in potassium chloride; the concentration of cadmium ions is $10^{-4} M$ (gramme-molecular weight per litre) in $0.1 M$ potassium chloride.



12. Polarogram for mixture of copper, lead, cadmium, and zinc ions in $0.1 M$ potassium chloride; the potential scale is reversed.

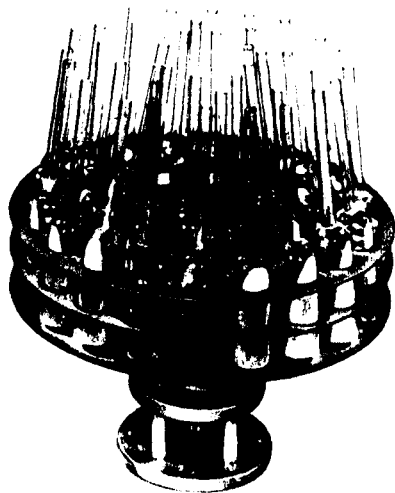
FREEZE-DRYING



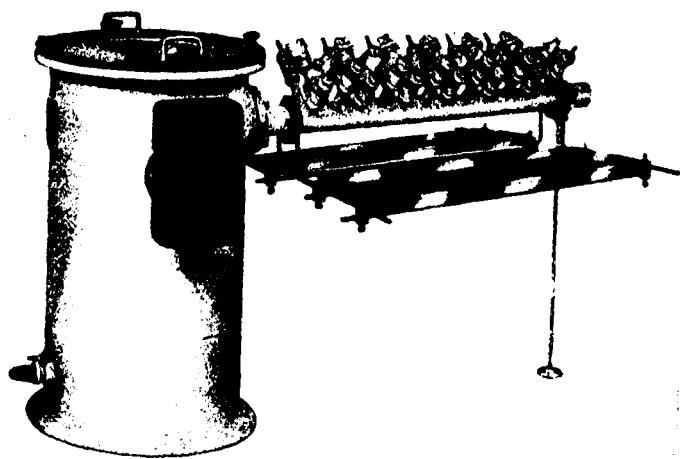
13. Polarogram showing the maximum due to copper ions in 0.1 M potassium chloride.



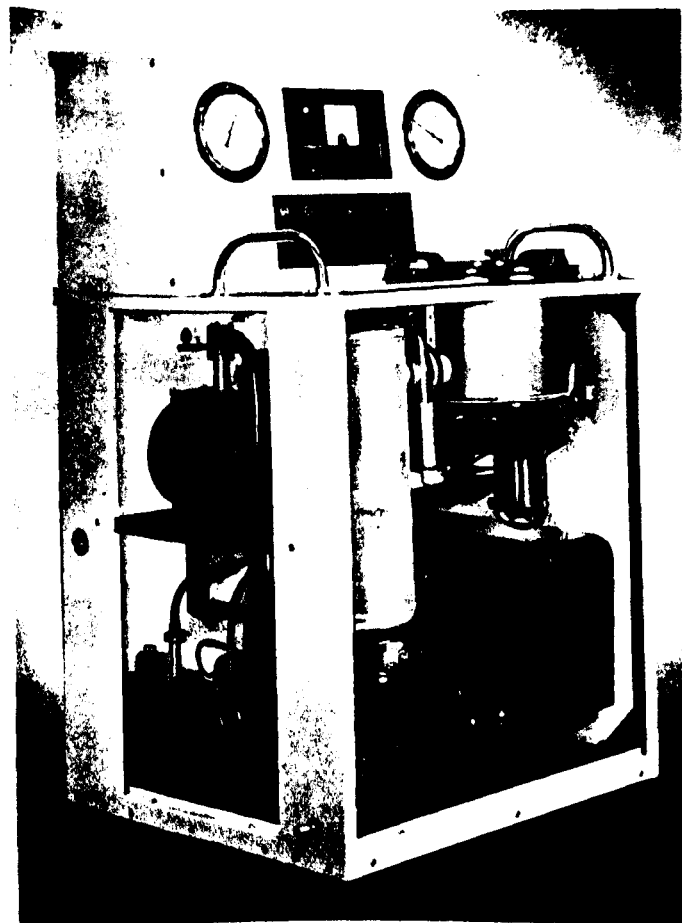
14. Drying chamber being loaded with racks containing small vials of antibiotics and bottles of plasma. (By courtesy of Dr E. W. Flosdorf.)



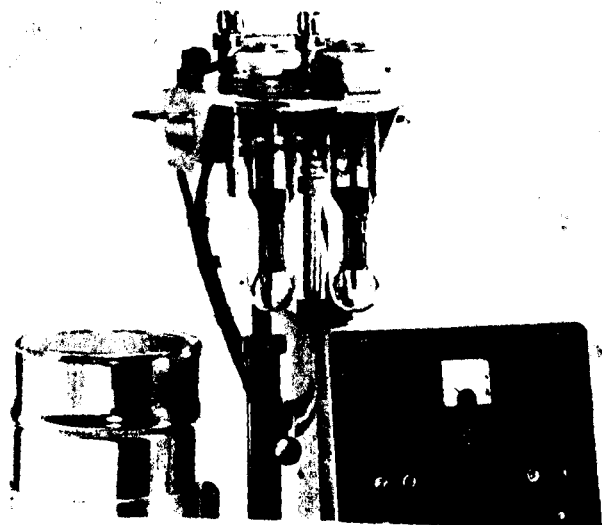
15. Single centrifuge head of centrifugal freeze-drier showing wedges of frozen material. (By courtesy of W. Edwards and Company (London), Ltd.)



16. Manifold type of unit with 'dry-ice' condenser. (By courtesy of Dr E. W. Flosdorf.)



17. Centrifugal freeze-drier of pilot-plant size. The following essential components can be seen: *inside* (lower part of unit), *extreme left* vacuum pumps, *centre foreground* refrigerated condenser for removing water vapour from the vacuum system, *bottom right* refrigerator unit for cooling the condenser, *middle right* drying chamber showing centrifuge drive-motor beneath; *instrument panel*, *left to right*, refrigerator dial thermometer, Pirani-type vacuum gauge, drying chamber dial thermometer. (This and the two following photographs are by courtesy of W. Edwards and Company (London), Ltd.)



18. Twin-head tissue drier: the drying tubes (*top centre*) are inside enclosures which can be held at any pre-selected temperature between -15°C and -50°C . The silvered-glass vacuum storage vessel (partly seen, *left*) contains a mixture of solid 'dry ice' and alcohol at -78°C , in which the drying tubes are immersed during drying.



19. Desiccators, vacuum pump, and vacuum gauge equipment for blood plasma freeze-drying plant having a weekly capacity of 500 litres.

volume of some reagent needed to complete the reaction with a known volume of the material to be determined. However carefully the critical last few drops may be added, the accuracy of the titration depends ultimately on the accuracy of the method used to determine the end-point. Such methods rely on following the acidity of the solution, its colour, conductivity, etc. In the method to be described one follows the limiting currents of one or both of the reagents that are reacting together in the solution. It can be most successfully used when the two reagents form a highly insoluble precipitate which is completely removed from solution. This is precisely the kind of reaction that is used in the more time-consuming procedure of gravimetric analysis, with all the nuisance of filtering off, drying, and eventually weighing. Polarography offers in principle the possibility of substituting the relatively quicker method of titration.

A titration between a lead solution and a dichromate solution can be carried out in a polarographic cell, the cathode of which is at -1.0 volts; both the lead and the dichromate ions then yield diffusion currents. An initial pure solution of lead will therefore yield a limiting current as we have seen in Figure 2. Successive additions of dichromate ions to the lead solution will precipitate insoluble lead dichromate, so decreasing the concentration of lead ions in the solution, and the diffusion current will fall, as shown in Figure 4. This decrease in current will continue until all the lead has been precipitated. Further addition of dichromate solution will now produce an increase in the current

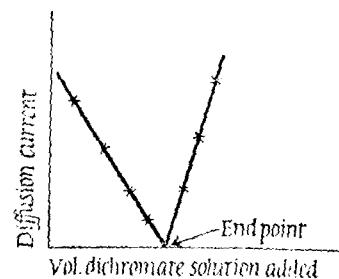


Fig. 4. Titration plot for lead-dichromate system.

flowing, because of the reduction of the dichromate to chromic ions at the dropping mercury electrode. A simple extrapolation of these two lines gives an accurate result for the end-point.

As with ordinary polarographic studies, metals can be estimated even if they are not reduced at the cathode. Thus I. M. Kolthoff and Johnson have devised an ingenious titration technique for the estimation of zirconium, a metal that does not yield a diffusion current. This method is based on the precipitation reaction between zirconium and phenylarsonic acid, $C_6H_5.AsO_3H_2$. This has been used for some years as a gravimetric method of estimating zirconium. These workers found that phenylarsonic acid does not give polarographic waves that are sufficiently reliable to use in this type of titration. If, however, a nitro group (NO_2) is introduced into the phenyl group, the resulting compound, *m*-nitro-phenylarsonic acid, gives well-defined polarograms. Successive additions of zirconium to this solution will precipitate the zirconium *m*-nitro-phenylarsonate, and its limiting current will decrease. From the graph obtained (see Figure 5) the end-point and the concentration of zirconium can be estimated.

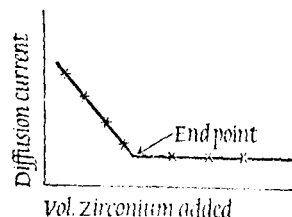


Fig. 5. Titration plot for zirconium-*m*-phenylarsonic acid system.

ORGANIC POLAROGRAPHY

Polarography may be applied to organic as well as inorganic systems, and many reducible organic compounds yield well-defined polarographic waves. Half-wave potentials for organic compounds vary very considerably with the acidity of the solution, and all work has to be carried out in solutions in which the

hydrogen ion concentration is rigidly controlled. This effect may be seen with nitrobenzene, a compound which in ethyl alcohol-water systems gives two waves, when the hydrogen ion concentration is greater than 10^{-5} (Table II).

TABLE II: Variation of Half-wave Potentials of Nitrobenzene with Acidity

Concentration of Hydrogen Ions	$E_{1/2}$ First Wave (volts)	$E_{1/2}$ Second Wave (volts)
10^{-1}	-0.22	-0.675
10^{-4}	-0.415	-0.975
10^{-12}	-0.83	—

One of the most interesting polarographic effects is that shown by proteins. Thus R. Brdicka, another early Czech worker in polarography, found that when small quantities of solutions containing protein were added to an ammoniacal cobalt solution, the wave corresponding to the reduction of the divalent cobalt ion was followed by two protein waves (Figure 6). These are due, not to the reduction of the protein, but to the evolution of hydrogen, catalyzed by the presence of the protein at the cathode surface. The height of these double waves increases with the protein concentration, though not in direct proportion to it. This has been used as a basis for the analytical determination of proteins, e.g. in small volumes of cerebrospinal fluid, urine, etc.

The amino-acids cystine and cysteine also show this reaction

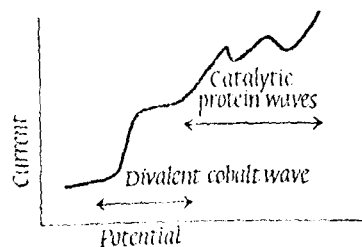


Fig. 6. Catalytic protein waves in ammoniacal cobalt solution.

and it is possible to determine the cystine content of a single hair in this way. The effect is thought to be due to a direct reduction of any sulphhydryl groups ($-SH$) present in the molecule, liberating hydrogen. The reduced ions react immediately with any acid present to re-form the SH group. This theory is confirmed by studies on denatured proteins from which it is known that the sulphhydryl groups have been liberated. These denatured proteins give catalytic waves that are larger than and different in shape from normal catalytic protein waves. The effect of denatured protein in cow and mouse milk sera has been found to be similar to that in blood sera.

Brdicka has shown also that a correlation can be drawn, in many cases, between the height of the catalytic protein wave obtained from treated human sera and the occurrence of cancer in the patient concerned. Much investigation has been carried out into the value of the polarographic technique as a possible diagnostic test for cancer. The growth, surgical removal, and regrowth of cancers can certainly be followed, but the technique is not 100 per cent positive.

RECENT ADVANCES IN POLAROGRAPHY

During the past few years, considerable advances in the technique and instrumentation of polarography have been made. In particular, various techniques have been employed in order to obtain derivative polarograms: that is, the quantity plotted is the slope of the original or normal polarogram. Since the slope is greatest at the half-wave potential, a peak appears at the half-wave potential on the derivative curve (Figure 7). Such polarograms are especially useful in the analysis of mixtures of metals whose half-wave potentials are so close together that their waves coalesce.

Two French workers, M. P. Leveque and F. Roth, have developed a simple circuit that gives derivative polarograms. This consists essentially of a high-capacity condenser in series with the recording galvanometer. In the regions AB and CD of the polarogram, where the current in the cell is nearly constant, little current flows through the condenser. During the rise in current

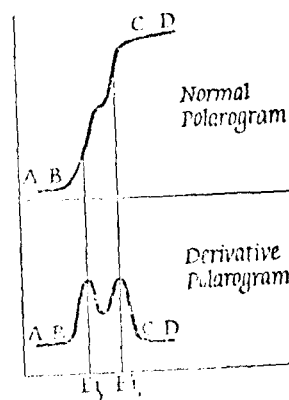


Fig. 7. Resolution of two coalesced waves using the derivative technique, in which the quantity plotted is the slope of the original or normal polarogram.

associated with the polarographic wave, however, the condenser will pass current and the galvanometer will be deflected.

A.C. Polarography

Derivative-type polarograms are also obtained when a small alternating voltage (0-30 millivolts) is superimposed upon the slowly-changing direct potential applied to the cell, and the alternating component of the cell is rectified and recorded. Here again, no deflexion of the galvanometer or pen recorder will be noticed during the time that the residual and limiting currents alone are flowing, for small variations in voltage over these portions of the polarograms produce little variation in current. During the rising portion of the polarogram, however, there will be an alternating component, and this will be greatest at the half-wave potential. This technique has recently been applied by B. Breyer and his Australian co-workers to the analysis of mixtures of metal ions at concentrations of $10^{-4}M$. These techniques, however, although giving greater resolution than normal polarography, do not reduce the contribution from the double-layer which also has an alternating component.

This problem of the condenser current has been successfully overcome in the square-wave polarograph designed by G. C. Barker and I. L. Jenkins at the Atomic Energy Research Establishment, Harwell. In this instrument a square-wave instead of a sine-wave alternating voltage is superimposed upon the cell (see Figure 8) and the current flowing is measured only at each change of the applied voltage. During the time of application of voltage, although the diffusion current remains practically constant, the residual current decays exponentially, almost to zero.

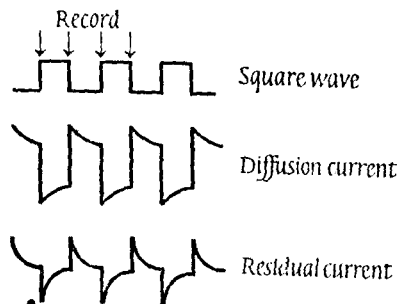


Fig. 8. To show the mode of operation of the square-wave polarograph.

No interference is therefore experienced from the residual current, and the current that flows can be amplified, permitting much smaller concentrations of reversibly reducible ions to be determined. This technique may be used to determine concentrations of ions as low as $2 \times 10^{-7}M$; it is thus 100 times as sensitive as conventional polarography. The square-wave polarogram reproduced as Figure 9 shows the sensitivity and resolution of the technique. The minor constituents of an aluminium alloy are seen clearly separated and the alloy can be readily analysed, even for the trace of cadmium which would be undetectable by normal polarographic techniques.

The Rotating Platinum Electrode

Although 99 per cent of all polarographic research has been

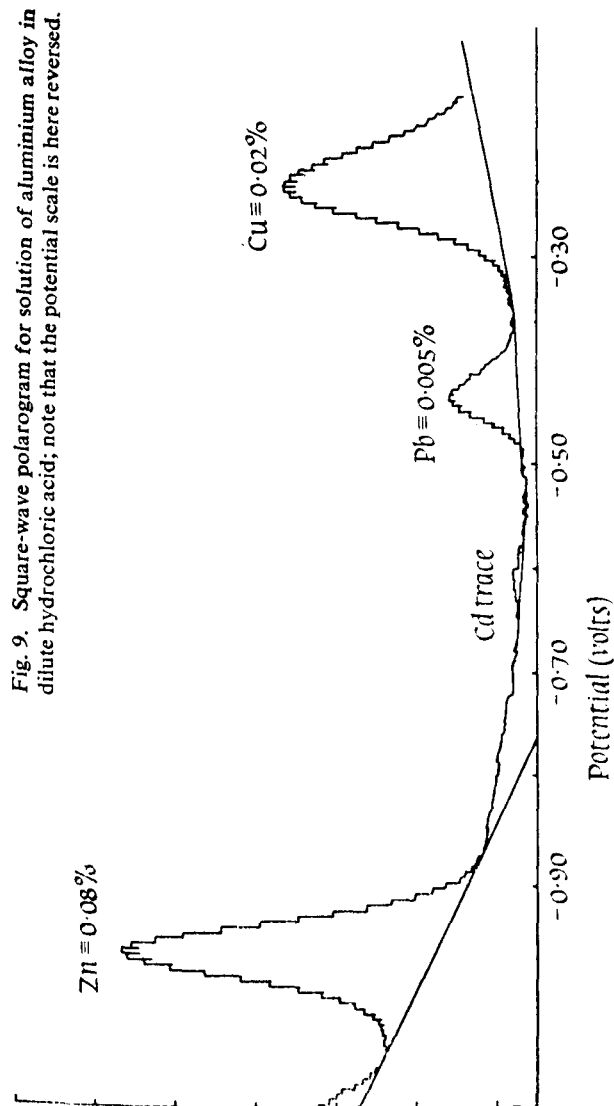


Fig. 9. Square-wave polarogram for solution of aluminium alloy in dilute hydrochloric acid; note that the potential scale is here reversed.

carried out with the dropping mercury electrode, H. A. Laitinen and Kolthoff and later workers in this field have been able to show that a rotating platinum electrode can also be used as a polarographic electrode. This electrode, as can be seen from Figure 10, consists essentially of a steel shaft to which the cathode connexion is made. At right angles to this is connected a piece of bright platinum wire, 0.5 millimetres in diameter and

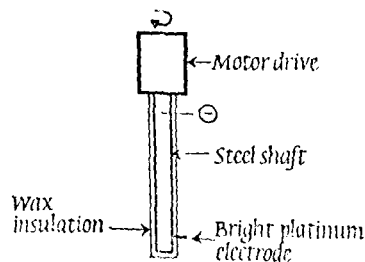


Fig. 10. Schematic representation of rotating platinum electrode.

3.5 millimetres long, which serves as the electrode. The steel shaft is insulated by a protective coating of wax, and is rotated at 600 revolutions per minute in the solution. This electrode behaves as a polarographic electrode, with some additional advantages. Its sensitivity is some 20 times as great as the dropping mercury electrode, since rotation of the electrode decreases the thickness of the diffusion layer, d in Equation 2; the polarograms are smooth and therefore more easily measured; and the electrode can be used in regions of positive potential where the dropping mercury electrode cannot be used. It suffers, however, from two disadvantages. Because of the low reduction potential of hydrogen on a platinum surface it cannot be used at potentials greater than -1.0 volt, and therefore for the analysis of many metals. Secondly, its surface cannot be renewed – which was the attraction, in the beginning, of the dropping mercury electrode, and which is still the main reason for the usefulness of this electrode.

FURTHER READING

This review has been able to sketch only in broad outline the main features of polarographic technique and applications. The most comprehensive text-book in English at present available is the American monograph:

Kolthoff, I. M., and Lingane, J. J. *Polarography*. New York. Interscience Publishers, Inc. 1952.

The above covers extremely well all polarographic literature up to 1951. G. W. C. Milner and J. E. B. Randles are publishing a text-book *The Principles and Applications of Polarography* (London: Longmans, Green & Co.) in the spring.

The review article by Brdicka, mentioned in the text, is in *Research*, 1, 1 (1947).

ADAPTATIONS IN DIVING MAMMALS

R. J. HARRISON

MAMMALS which have become adapted to spending the whole or the greater part of their lives in the oceans swim for longer periods under water and dive to greater depths than do land-living mammals. Anatomists have therefore frequently been fascinated by the various modifications in the structure of marine mammals, and by the problem of relating these to performance. The duration of a dive raises questions about oxygen supply and consumption. Dives of long duration might, on first thoughts, be expected to be favoured by a greater initial supply of oxygen; certainly by economy in its consumption while submerged, and – up to a point – by ability to withstand a low concentration. Such considerations suggest that the answer to these problems may be concerned primarily with modifications in the circulation of the blood, although there are other factors which may arise. For example, economy in the use of oxygen is helped incidentally by a high mechanical efficiency in swimming, and this is, in fact, found in diving mammals. But it could also be helped by a curtailment of metabolic activity which is inessential during the period of diving. The second type of performance, the ability to dive deep, implies an immunity from troubles caused by the reduced pressure of dissolved gases when coming to the surface – the cause of the caisson sickness experienced by divers.

Two major obstacles are encountered in working on the great majority of marine mammals; the frequently large size of the specimens renders dissection somewhat of a labour and almost precludes experimentation except on the smaller species, and the difficulties of collecting dead material or catching live specimens usually mean at least a small expedition to obtain them.

It is not therefore surprising that many of the previous accounts of the anatomy of Cetacea have been made from dissection of foetuses of the large species or of adult dolphins and porpoises (and even they are difficult to come by in any number), and that most of the recorded physiological facts have been obtained from experiments mainly on the Common or Harbour Seal (*Phoca vitulina*) from among the seals, sea-lions, and walruses (Pinnipedia). Limited observations have also been made on beavers and otters, the manatee and the hippopotamus.

As might be expected, John Hunter's *Observations on the Structure and Oeconomy of Whales* (1787) may perhaps be considered to be the first serious description of the anatomy of whales, whilst Burow's *Über das Gefässsystem der Robben* (1838) is the earliest account of vascular modifications in seals. Hunter's physiological observations are naturally somewhat limited and one reads only of speculations such as his statement that 'ten or fifteen gallons of blood are thrown out of the heart at a stroke, with immense velocity'. Reading the early writers in search of quantitative observations is only likely to result in finding such remarks as: 'the aorta of a whale is larger in the bore than the main pipe of the water-works at London Bridge, and the water roaring in its passage through that pipe is inferior in impetus and velocity to the blood gushing from the whale's heart.'

There are not many accurate observations of the submarine habits of whales and seals, of how deep they usually dive, of how long they normally stay submerged, or of how far they can swim beneath the surface of the water during a dive. It is at any rate fairly clear that many early estimates, such as some of those quoted by Herman Melville, were, as he suspected, somewhat exaggerated or were based on exceptional performances made by animals terrified by hunting. The full-grown bull sperm whale, which occasionally can grow to over 60 ft in length, remains on the surface for about 10 minutes, during which time it makes sixty or so respiratory excursions, and then submerges for about an hour. Rorquals, or Finner Whales, proceed through the water in a series of shallow dives in more or less rapid

are voluminous retia in the chest, spinal column, and head; incidentally one of the few places, if not the only one, where dissection of these retia may be seen is in the Whale Hall of the British Museum (Natural History). There the late R. H. Burne's beautiful dissections, made between 1935 and 1941, of the retia of porpoises and other toothed whales are carefully preserved.

There has been considerable discussion as to the function of these retia, a discussion generally related to their association with the particular habits of any animal. Not only are retia found in marine mammals, but also in varying degrees of complexity in representatives of nearly all mammalian groups. Retia are particularly developed in the extremities of sloths, two-toed ant-eaters, and lorissine lemurs, all being arboreal animals and characterized by their extraordinarily slow movements. For over a century these vascular modifications have been associated with this strange slowness of movement, but, as D. W. Fawcett has strongly emphasized, the porpoise is one of the fastest swimmers known, and it possesses similar vascular structures.

Suggestions that the retia act as oxygen stores have been proved wrong, and R. Walmsley has put forward the consideration that they are vascular adaptations to changing lung volume at the varying pressures encountered during diving. He supports his contention with the observation that the retia are most developed in the whales that dive deepest, yet they are considerably developed in porpoises, that do not dive deep or stay submerged for long periods. The problem will be further considered after the other vascular modifications encountered in diving mammals have been described.

All the veins in the abdomen of seals are considerably dilated and are surprisingly thin-walled: Figure 1 shows the general disposition of the main veins and venous reservoirs. The inferior vena cava is duplicated in all Pinnipedia and is shown in Inset 3 and 5; the late Professor F. Wood Jones once remarked that the two limbs of the inferior vena cava of a full-grown walrus could be drawn over the legs like a pair of trousers. There are, however, numerous cross-connexions between the two limbs.

The kidneys in Cetacea and Pinnipedia are multiple organs

Adaptations in Diving Mammals

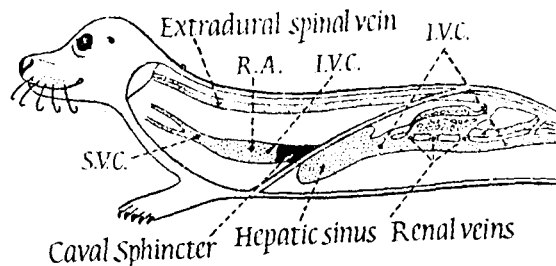


Fig. 1. Diagram to show the disposition of the main venous channels and reservoirs in the seal. (R.A. = right atrium of the heart; I.V.C. = inferior vena cava; S.V.C. = superior vena cava.)

consisting of many (in whales up to many hundreds) small units or renunculi, each draining by separate openings into numerous cup-shaped receptacles (calyces) and then by short channels into the typical mammalian single ureter. Inset 6 shows the form of the calyces. In Pinnipedia the venous drainage of the kidney is to a stellate plexus of veins on the surface of the organ (Inset 3). This plexus communicates widely with the posterior abdominal veins, a system of veins in front of the spinal column (the azygos system), the pelvic veins, as well as draining by three main renal vessels into the respective limb of the double inferior vena cava. The renal plexus also communicates by three or more large channels with a large vein lying within the spinal canal at the back of the spinal cord. This interesting vein will be described fully later. The Cetacean kidney is also built up on the compound pattern (Inset 7), and although there is a less developed stellate plexus of veins on the surface of the organ, it appears that the typical mammalian renal vein leaving the root of the organ is also present and that the stellate plexus drains into the renal vein and does not have the widespread communication of the seal. At least such is the conclusion from examining foetal specimens, and it may well be that the stellate plexus and its communications become enlarged and more important in the adult.

It has occasionally been asked whether the multiple nature of

the kidney and its stellate plexus are associated with any adaptations in renal function. The opportunities for drinking fresh water must be limited unless the whales or seals enter estuaries, and it has been argued that the total water intake must be derived from sea-water and the water contained in the food material, be it fish, squid, or plankton. Seals, at least, are known to like drinking fresh water and will drink a bucketful rapidly. Investigations of the blood biochemistry have so far only revealed results which fall within the known mammalian range. There is, however, evidence that the urinary concentrating mechanism is highly developed in seals and that the filtration rate is markedly elevated by feeding and is greatly reduced on diving or on excitation of the diving reflex.

The main veins of the liver in the Pinnipedia are considerably dilated and are fused together to form a large sinus in the part of the liver below the diaphragm; it is known as the hepatic sinus (Figure 1 and Inset 5). This is relatively thick-walled because of the presence of muscle fibres, and can hold nearly a litre of blood in an adult Common Seal. The abdominal inferior vena cava enters this sinus on the right and blood from this vessel is joined by that passing through the hepatic veins. The end of the inferior vena cava leaves the apex of the sinus and at once passes through the diaphragm. Immediately above the diaphragm a band of muscle about 2 to 3 centimetres in length and 0.5 centimetre thick surrounds the first part of the thoracic inferior vena cava in the form of a distinct contractile muscle girdle or sphincter. It is innervated by the same nerve that supplies the diaphragm, the phrenic nerve, and is composed of striated voluntary muscle fibres arranged circumferentially. It is known as the caval sphincter (Figure 2) and is present in all species of Pinnipedia examined; it is also found in the otter and the hippopotamus, and although said to be present only in the porpoise among Cetacea, the author has seen a sphincter in foetuses of some other species of whale. The credit for its discovery is often attributed to R. H. Burne, but in fact it was described nearly eighty years earlier by Burow in 1838. The sphincter can be seen in an Antarctic seal embryo in Inset 4.

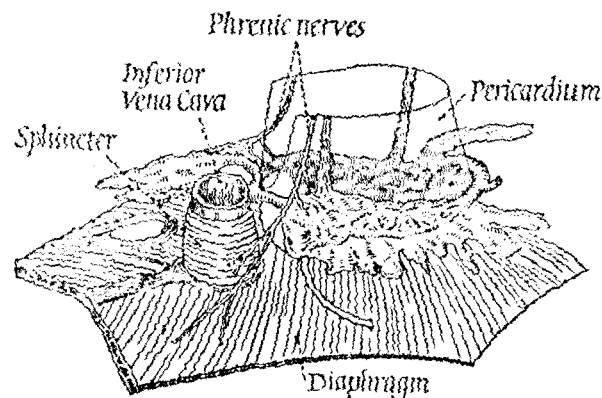


Fig. 2. Diagram showing the muscular girdle or sphincter on the inferior vena cava of the seal and the venous plexuses draining into it.

Immediately above the free edge of the caval sphincter in the seal, and in the otter, one or more veins are given off and enter a plexus of vessels surrounding the heart. This plexus forms a series of fringe-like projections into the cavities containing the lungs, and were it to be dilated with blood it could reduce the volume of these cavities. The plexuses surrounding the heart contain branches from the phrenic nerve and also small arteries. The veins of this plexus have muscular walls, with the muscle fibres arranged in a spiral fashion and supported by coiled fibrous strands arranged circumferentially. It thus appears that this plexus is capable of considerable dilatation and it is quite easy to inject over 200 millilitres of fluid into part of the plexus after death. Preliminary investigations have not proved that this plexus can function as a baroreceptor, i.e. that it is sensitive to changes in pressure and capable of transmitting such information.

Some excellent casts of the vascular system of the seal have recently been prepared by J. D. W. Tomlinson, using various plastics. These preparations, besides illustrating the vascular

modifications already described, have shown very clearly the presence of a large vein lying within the spinal canal external to the spinal cord and its surrounding membranes, and extending the whole length of the vertebral column: its position is shown in Figure 1. This vein lies outside the dura mater and has numerous connexions with other venous systems. There are two main vessels passing from this extradural vein, which is usually double in the neck, through a bony canal to join the sinuses within the skull. Numerous vessels connect the extradural vein to a large plexus of veins below the skull, and also to the other important veins in the chest. Three or more large communications pass between the vertebrae of the lumbar region to join the renal plexuses and lumbar veins on each side. As a result of the existence of this extradural vein and its connexions, it is anatomically possible for blood to pass from inside the skull to the renal plexus, and perhaps vice versa. Experiments have proved that there is wide and free communication along this pathway in both directions.

In the whales no such enlargement of the veins of the liver into a hepatic sinus has yet been described, and, as has been seen, a number of species at least do not possess a muscular girdle around the inferior vena cava. The arrangement of the veins in the spinal canal in the four species of whale examined by ourselves and others is quite different from that found in the seals. In the whale there are two longitudinal venous channels (Inset 8), relatively small in calibre in the foetus but perhaps larger in the adult, lying beneath the spinal cord and extending only as far headwards as the upper part of the chest. They are linked by cross-channels, one to each vertebra, and they also communicate with an extensive capillary plexus extending throughout the dura mater, the membrane surrounding the nervous system. In the whale foetuses examined no large extradural vein comparable to that in the seals has been found. In the Blue Whale, *Balaenoptera*, the intravertebral veins are connected to the lumbar and intercostal veins, and in the chest region these communications drain into a large, longitudinal vein, which lies in front of the vertebrae. Headwards from the termination of

the intravertebral vein into this posterior thoracic vein there is a complicated vascular plexus surrounding the spinal cord. This forms a 'rete mirabile' which is in communication with the large, intracranial rete in this animal.

It must not be thought that the extradural veins, well marked and enlarged as they are in the seals, are restricted to those mammals, or even to marine mammals. Such a venous system can be found, more or less well developed, either as a single vein or as a plexus, in the sloths, the slow loris, and the otter, as well as in many Cetacea, manatees, and seals. In these animals the inferior vena cava is usually duplicated, and the two limbs have large connexions with the intra-spinal veins. Furthermore, it has recently been emphasized that in monkeys and in man there is a plexiform network about the vertebral column having numerous connexions with the extradural veins in the spinal canal and with veins of the thoraco-abdominal wall. Batson has considered the function of this system in man and strongly suggests that it is a system used for storage and also as an effective by-pass for the main caval system during any act of straining, particularly of the thoraco-abdominal wall. It is perhaps not surprising that these connexions are particularly large in the human child, thus avoiding over-embarrassing the heart when the child throws a prolonged fit of tantrums and muscular contortions on the floor when objecting to the demands of parental authority. Later in life, when the vertebrae have hardened and these communicating channels are probably narrower, it becomes too exhausting, and perhaps dangerous, to indulge in such tantrums. These observations are relevant to the problem of diving in that submergence must involve muscular exertion with the airway closed. There will also be the additional factor of hydrostatic pressure, increasing as the animal dives deeper and compressing more and more the contained air. But it should be clear that in seals, at least, which dive after expiration, once the residual air has been expelled from the lungs into the more rigidly protected part of the respiratory tract, the effect of hydrostatic pressure will be considerably reduced and perhaps even be negligible. Harrison Matthews has argued that, if a diving mammal is able to expel

air from its lungs into the rigid air passages so that it can virtually allow those organs to collapse and become solid, there is no reason why it should not dive to any depth. The animal becomes, as it were, like a submarine nearly filled with water (and water is virtually incompressible) with the air inside the submarine compressed within a small and rigid container.

G. B. Wislocki and his collaborators have also made a study of the microscopic structure of the lungs of whales of various sizes. They find the large air passages in all Cetacea to be enclosed throughout by fused links of cartilage. The air sacs are excessively large and each air sac has a capillary network of its own; thus the lung septa are lined by capillaries on each side. Elastic muscular bundles of varying size and heaviness are found in the septa projecting into the air sacs, and an elaborate system of elastic muscular sphincter around the smaller air passages is a characteristic of the smaller whales. It is probable that the muscular component of these bundles provides, in the larger whales, a powerful mechanism for closure of the air sacs, and that the elastic component contributes to rapid evacuation of air during expiration. Several observers have commented on the high efficiency of the ventilation of the lungs during spouting. Some of these anatomical characteristics are found also in the lobulated lungs of seals; another characteristic of the latter is the presence of numerous multiple mucous glands, found in relation to the air passages. These glands are large and are placed outside the cartilages, and they pour their secretions into the air passages by ducts passing between the cartilages. The lungs of seals are also interesting in that there is a marked network of thick-walled arteries and thin-walled veins lining the cavities containing the lungs; injection experiments have shown that these vessels send their branches extensively throughout the lung and are obviously related in function to the bronchial arteries.

During the last 15 years much interesting information has been obtained on the physiological behaviour of seals during diving, and some observations have also been made on the behaviour of beavers and the porpoise. This is known as the result

particularly of the work of Laurence Irving, P. F. Scholander, and their collaborators; some experiments have also been carried out personally in collaboration with J. D. W. Tomlinson and L. Bernstein.

Irving and his collaborators carried out experiments in which seals were fixed to a board with the head and hind-flippers slightly elevated. The board was suspended in a bath-tub with the nostrils and the hind-flippers of the animals above the water. In this position the seal would lie quietly for many hours and would apparently go to sleep. To produce an experimental dive the head end of the board was simply tipped below the surface of the water. By such methods it could be shown on an electrocardiograph that there is an immediate drop in heart rate on diving from 150 beats per minute to 10 beats per minute. This slowing of heart rate persists during the whole of the dive and is apparently unaffected by any activity on the part of the animal. Despite it, the arterial pressure, as recorded in the leg artery, remains unchanged, and is maintained by the continued constriction of the small arteries, apparently under reflex control. The vessels of the gut also contract and thus, together with that vascular adjustment, the reduction in blood flow to the periphery makes possible the continuity of circulation of important tissues, such as the brain, during the period of heart-slowness. Immediately after the dive the heart rate returns to normal during the period of recovery.

It is not known for certain if the heart rate in diving whales shows the marked slowing known to occur in diving seals; inconclusive experiments on porpoises did not show any such slowing, and in any event such experiments would be difficult to carry out conclusively on larger whales. In seals, however, it is fairly certain that slowing occurs during any type of dive, and in view of the time spent submerged it is not surprising that a number of workers should have been puzzled by the apparent continued functioning of the brain over such long periods.

The oxygen content of the arterial blood of the seal was found to drop at a fairly constant rate during diving; at the beginning of the dive oxygen content is about 20 per cent, and when it has

fallen to about 2 per cent the seal has to return to the surface or it will die. The fact that there is a pronounced slowing of the heart and narrowing of small arteries will retard oxygen consumption and thus prolong the dive.

It is known that before seals embark on a deep dive they blow a large quantity of air from their lungs; on shooting at a seal in water a near-miss results in forcible expulsion of air and bubbles mark its precipitate 'blowing-off'. As a seal submerges deeper the residual air left in the lungs will be compressed, owing to the increased water pressure. The diaphragm in the seal is arranged in a particularly oblique manner, and will be pushed headwards and backwards by the abdominal contents, so that residual air in the lungs will be forced into the respiratory passages. It has been suggested that the muscular elastic valves already described prevent escape of air during diving, enabling the animal to modify its buoyancy by retaining or releasing air. However, it appears much more likely that these valves contract after the air has been expired into the upper part of the respiratory passages and thus provide a further mechanism for preventing the absorption of nitrogen into the blood. Any animal or human being diving to a depth of 45 ft or over is liable to suffer from caisson disease, or the 'bends', on returning to the surface. At that depth the pressure is sufficient to cause nitrogen to pass into solution in the blood and fat, and perhaps other tissues, and then on return to the surface to cause gas to come out of solution, forming bubbles in the blood vessels and thus be the cause of their obstruction.

A number of experiments have recently been performed in seals by the author and his collaborators in order to investigate the functional significance of some of the anatomical facts described above. In one experiment a seal pup was anaesthetized and the lung and abdominal cavities were opened, and the right phrenic nerve and the contractable girdle on the inferior vena cava, the caval sphincter, were found. An opening was made into the anterior wall of the large sinus of the liver and a cuffed tube was inserted through the sinus and passed up the inferior vena cava so that the cuff lay within the sphincter. On stimula-

tion of the phrenic nerve it was possible to record the contraction of the sphincter about the cuffed tube. The sphincter contracted whenever the phrenic nerve was stimulated, and the diaphragm contracted at the same time. On cutting the branches to the diaphragm the sphincter alone contracted. After cutting the left phrenic nerve and stimulating the central end of the nerve, no contraction of the sphincter was recorded. During normal respiration under anaesthesia no marked contraction of the sphincter was observed or recorded.

In another experiment on an anaesthetized animal radio-opaque material was introduced into one of the renal veins and allowed to pass towards the heart. The phrenic nerve was then stimulated and it was shown radiologically that the sphincter is capable of shutting off the venous return from the liver sinus to the right side of the heart. X-ray films taken during the process of this experiment are illustrated in Inset 9 and 10. It is interesting to note that in this experiment the plexuses round the heart, supplied from the inferior vena cava by vessels leaving it headwards from the sphincter, were not filled. This perhaps implies that they are only filled during diving. It was also possible to introduce a needle into the large extradural vein and after introducing some radio-opaque material it was shown radiologically that this material passes into the venous sinuses of the skull and into the abdomen very easily and at almost the same time. Further experiments were carried out in which radio-opaque material was injected into the arterial and venous systems of the head and neck of the seal, and from these experiments, and also from injection preparations, it is clear that the jugular system of veins is not well developed; thus it appears that the main venous return from the skull is by the extradural vein, and that during a dive blood passes from the heart, through the head and neck, and returns to the abdomen mainly via the extradural vein. The large veins and venous plexuses in the abdomen provide ample space in which blood can accumulate.

As long ago as 1884 Professor J. Cleland, of Glasgow University, wrote that it seemed to him that the amount of blood in seals and whales was enormous in proportion to their size. It

appears that his belief was not unfounded, since recent estimations of the blood volume in seals, albeit in pups, gave a figure of about 120 millilitres of blood per kilogramme of body weight, by the Evans Blue method, and this in a newborn pup which had not put on the precocious deposition of fat which occurs during the period of lactation. (The adult human blood volume is about 80 millilitres per kilogramme.)

L. Irving and P. F. Scholander with their collaborators have made further valuable observations on the physiological behaviour of seals during diving. Their work is too extensive to review here apart from its general conclusions. The seal is apparently relatively insensitive to increased carbon dioxide in the blood; the oxygen consumption during diving is lowered to about one third of the normal level and remains thus lowered until the animal is practically exhausted. It is not yet known if there is a reduction in metabolic processes during diving, but it is apparently clear that when the oxygen tension has fallen to about 2 per cent, the seal must return to the surface or drown. Blood removed from veins in the hind-flippers was found to be nearly arterial in oxygen content, suggesting that when not diving there may be a high degree of arterialization of the large amount of venous blood. It should thus be clear that there are numerous anatomical and physiological adaptations enabling marine mammals to remain submerged at considerable depths, but for limited, though relatively long, periods of time; yet there are still many unsolved problems connected with how they do it.

Both whales and seals have an acute sense of hearing, and since it is known that whales, at least, emit noise under water, the auditory mechanisms are at present the subject of much investigation. It has been suggested that the noise is produced by small quantities of air being allowed to escape through the blowhole. F. C. Fraser and P. E. Purves of the British Museum (Natural History) are engaged in proving that whales hear in the normal mammalian manner with certain anatomical modifications necessary to receive water-borne sounds. They have made plastic injection preparations to show that the pharyngotympanic (Eustachian) tube connecting the ear and throat com-

municates with a system of pneumatic sinuses peculiar to the whales. In the porpoises a large air sinus fills a fossa beneath the skull and in beaked whales and dolphins this sinus is so enlarged that it covers most of the base of the skull as well. Extensive venous plexuses are also associated with the air sinuses and there is apparently some evidence of a reciprocal degree of filling of the air sinus and the venous plexus. The plexus is also associated with fatty tissue and it is suggested that the fat and the mucous membrane of the sinuses may have a gas-secreting function and may play a part in absorbing nitrogen. The air sinus may more certainly play a part in accommodating the pressure on the inside of the ear drum to that experienced on the external surface.

A consideration of reproduction and pregnancy in whales and seals is not without its problems; for example, does the foetus suffer anoxia should the pregnant cow dive deep and for a prolonged period? Several years' observation of pregnant seals does not lead to a belief that their diving powers are impaired, although it is impossible to assess if pregnancy prohibits diving to any great depth. Should a cow be disturbed on a beach or sandbank in the very short first stage of labour she can apparently interrupt the process at will, take to sea and swim to another bank or return later when the danger has passed. It is not known if whales possess this power, since they give birth while swimming.

Some specimens of pregnant uteri and recently shed placentae of seals have been examined in collaboration with E. C. Amoroso and L. H. Matthews. Although the early development of the placenta is interesting, particularly in regard to the fate of the yolk sac, there appear to be no modifications during early pregnancy which can be clearly correlated with diving. In the full-term placenta, however, there are numerous small vesicles on the foetal surface of the placental band, into many of which enlarged maternal sinusoids have erupted, giving rise to numerous pockets of maternal blood. Such occurrences are not unknown in the placentae of other mammals, but the fact that the maternal sinusoids near the foetal surface of the placenta appear excessively enlarged may be associated with the general

enlargement of veins found in the animal, and may thus be associated with diving.

It is also known that seal pups are born with the gonads considerably enlarged and with the reproductive tract generally showing evidence of having been stimulated to precocious activity. Such precocious activity in the foetal reproductive organs is also known to occur in the mare, but at a different stage of foetal development, and it is not yet certain that these changes are associated with living in a marine environment.

FURTHER READING

Many references to original work will be found in the following:

- Franklin, K. J. *A Monograph on Veins*. Springfield, Illinois, C. C. Thomas, 1937.
- Harrison, R. J., Matthews, L. H., and Roberts, J. M. 'Reproduction in Some Pinnipedia.' *Transactions of the Zoological Society of London*, 27, 437 (1952).
- Howell, A. B. *Aquatic Mammals*. Springfield, Illinois, C. C. Thomas, 1930.
- Matthews, L. H. *British Mammals*. London, Collins, 1952.
- Norman, J. R., and Fraser, F. C. *Giant Fishes, Whales and Dolphins*, London and New York, Putnam.
- Scholander, P. F. 'Experimental Investigations on the Respiratory Function in Diving Mammals and Birds.' *Hvalrådets Skrifter*, 22, 1 (1940).

FREEZE-DRYING

R. J. C. HARRIS

THE fact that proteins are more stable when dry than wet has been recognized from early times in the practice of drying fish and meat to provide reserve stores of food. Moisture is indeed one of the two chief enemies of chemical stability, the other being heat. Drying by any process involves the removal of water from solutions, and to effect this there must be an input of energy, usually as heat. There is therefore a risk that, in drying for long-term stability, one may in the process bring about those very changes which one hopes to prevent. But although energy must be expended to remove water from solutions, this can be done at low temperatures as well as at high ones. Water may be removed from a frozen solution or suspension by sufficiently reducing the pressure above it. The ice then sublimates without thawing. This effect was applied to the preservation of biological materials as long ago as 1909, and the method was developed for large-scale use shortly before and during the second world war. It is still finding new uses, two of the most recent being the preservation of tissues for use in surgical grafting and the preparation of specimens for electron microscopy. It is known as drying by vacuum sublimation or, more commonly, as freeze-drying.

Freeze-drying is an expensive method of desiccation, but it is the best method for preserving such protein-containing materials as blood sera or plasma, some hormone preparations, bacteria, viruses and moulds, vaccines, human milk, and drugs, such as the antibiotics, which tend to be unstable to more simple but drastic drying procedures. In most of these examples, the primary cost of the product is high, and it is therefore worth while to choose the optimum method of desiccation irrespective of cost. On the other hand protein-containing materials can be

dried satisfactorily enough for some purposes by other methods. For example, roller or film driers have been used to produce dried milk, and spray-drying, where very fine drops of the liquid are sprayed into a hot, dry air current, has been used for drying milk, coffee extract, and even human blood sera and plasma for transfusion. In these processes, the relatively high temperatures used are compensated by the short time for which the materials treated are exposed to them.

Since freeze-drying involves the freezing of the solution or suspension, it may legitimately be asked: Why trouble to remove the water? Are not frozen materials effectively 'dry'? It is true that at fairly low temperatures bacteria, viruses, and even larger organisms may be preserved under conditions in which it is certain that all water is in the solid state. All metabolic processes, and those which at higher temperatures tend to cause deterioration, are then at a standstill. However, storage under these conditions requires adequate, and carefully maintained, refrigeration, and it is one of the great advantages of freeze-drying that properly dried substances may be stored at normal temperatures in sealed containers.

TABLE 1: Relationship between the Temperature of Ice and Vapour Pressure

Temperature ° C	Vapour Pressure mm. Hg.
0	4.58
-10	1.96
-20	0.78
-30	0.29
-40	0.1
-50	0.03
-60	0.007
-70	0.001
-80	0.0004

It is not generally known how readily water vapour can be pumped off ice even when this ice is at a low temperature. Table I shows the relationship between the temperature of ice and the

vapour pressure of water in equilibrium with it. If the pressure over ice at 0° C is reduced below 4 millimetres of mercury, the water will be removed from the ice as vapour without passing through a liquid phase (i.e. it will sublime).

Proteins in solution, such as blood plasma, tend to be unstable to heating, as has been said. This destructive process is known as 'denaturation', and is best and most frequently illustrated by the coagulation by boiling of the soluble proteins of egg white. 'Denatured' proteins are usually insoluble and have lost some or all of their specific properties, retention of which is often essential. When a protein solution is dried by sublimation, the protein and salt molecules are left in a sponge-like skeleton occupying a volume equal to that of the original liquid. The forces which tend to produce 'denaturation' are minimal, and the dry product rapidly and completely dissolves when water is added.

THE DEVELOPMENT OF FREEZE-DRYING

The development of freeze-drying as a technical process has followed a rather complicated course, essentially because both freezing and the removal of water vapour can be effected in a number of ways. Freezing may be brought about either by direct cooling or by making use of the latent heat of evaporation of the water first extracted. Water vapour may be removed either by pumping or by chemical or physical absorption. Further, it is necessary, if working on a large scale, to provide for heating as well as cooling - heating to compensate for the cooling which accompanies drying. For work on a small scale there is a choice between simplicity and cheapness on the one hand, and greater reliability and elaboration on the other.

L. F. Shackell in the United States was the first in 1909 to describe the freeze-drying process and to extend it to cover a wide variety of materials. He froze the protein solution in a suitable container and transferred it rapidly to a desiccator containing concentrated sulphuric acid as a drying agent. The desiccator was connected to a Geryk vacuum pump (giving a pressure of about 1 millimetre of mercury), and the rate of transfer of the water vapour from the frozen material to the concentrated

acid was great enough to ensure that the specimen remained frozen; that is, the latent heat of evaporation was provided by the specimen itself. Drying took place from the frozen, solid state and no liquid water was present. The dry product was readily dispersed in water and the reconstituted material had the properties of the original. Shackell was primarily interested in preserving sera, and rabies virus from the brains of infected rabbits, but he also applied the method to the drying of meat, fruit, and vegetables.

It was not until 1935 that Dr E. W. Flosdorf and his collaborators developed procedures which stimulated not only laboratory but also commercial interest in the technique. Blood serum was dispensed in individual ampoules and frozen by immersion of the ampoules in a bath cooled by solid carbon dioxide to -78°C . These small containers were then attached to a manifold constructed either of glass or metal. A condenser cooled to -78°C by a similar bath was interposed between the vacuum pump and the manifold, and the water vapour was trapped there on its journey from the frozen serum to the pump. When all the ice had thus sublimed the little ampoules of dry serum were sealed off individually without breaking the vacuum (Inset 16). At -78°C , ice has a vapour pressure of 0.00056 millimetre of mercury. The dried sample, therefore, in its sealed ampoule at room temperature, is in contact with water-vapour at this pressure which gives a residual moisture content of less than 0.1 per cent.

It is possible to dispense with initial freezing in a low temperature bath and to freeze the solution *in situ* by evaporation. This procedure, which was first investigated by Dr R. I. N. Greaves at Cambridge, uses the latent heat of evaporation of the initial liquid water to cool, and freeze, the bulk of the product. This operation is complicated by frothing of the liquid as the pressure is reduced, but the frothing, which is due to the rapid escape of dissolved gas, can be controlled by reducing the pressure slowly, and as the pressure is further reduced the gas-free liquid tends to freeze completely and suddenly.

Subsequently, in 1938, Flosdorf published a method using a

chemical desiccant instead of a cooled condenser. The desiccant 'Drierite' removed the water vapour by forming a chemical hydrate (actually calcium sulphate hemi-hydrate, $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$). Spent desiccant could be regenerated by heating, giving an equipment which could be taken to places where solid carbon dioxide was not available. The original unit has been in use in Kenya since 1938 for the production of dry rinderpest vaccine. Obviously, prefreezing is precluded in such a method and 'vacuum-degassing - self-freezing', as introduced by Greaves was, therefore, adopted.

Other chemical desiccants which have been used include phosphorus pentoxide, which is far too expensive commercially but is frequently used in laboratory-scale driers, and silica gel. This is a regenerable desiccant, but at normal temperatures it has a low absorptive capacity and large containers are required. However, if the gel is cooled to -20°C , its efficiency is much increased. Silica gel cooled by mechanical refrigeration has, in fact, the same water-removing efficiency as a cooled condenser coil operating at a much lower temperature.

Attempts have also been made to introduce continuous condensers to overcome the difficulties which arise in batch processing, whether from the need to 'defrost' a cooled condenser or to renew the charge of a chemical desiccant. One form of continuous condenser employed a large metal tube cooled on the outside. Ice condensing on the inner surface was detached by scraper blades, and fell into a cold collecting chamber. An ingenious liquid condenser has also been designed for use with a moving-belt type of freeze-drier. A cooled salt solution is sprayed into the vacuum chamber and the water vapour condenses in it. The dilute salt flows out of the vacuum chamber, is reconcentrated by heating, cooled again, and recirculated into the chamber.

Historically the next development was a digression into the difficult technique of direct pumping both to remove water vapour and to bring about freezing. Most vacuum pumps are oil-sealed and, as all those who have ever got water into the oil will know, they lose their efficiency when the oil is thus con-

taminated. In Flösdorf's equipment the water vapour was actually condensed in the pump oil, but the oil was continuously clarified in a centrifuge so that water-free oil was returned to the intake side of the pump. Multiple steam ejection pumps have also been used for direct water vapour pumping. These work on the same principle as the laboratory water pump, but use steam instead of water. Where, but only where, high pressure steam and large amounts of condenser water are very cheap, such steam pumps are still used. Both these systems have now largely been superseded by mechanically-refrigerated condensers, and these are now used both on the laboratory and on the commercial scale.

As soon as freeze-drying began to be used in the production of large numbers of single-size containers having the same product, manifolds on the 'sow and piglet' system (Inset 16) became so complex as to be both expensive and prone to leak. They were then replaced by vacuum chambers (Inset 14) which brought their own problems. The difficulty was that on the manifolds the drying product received heat from the atmosphere, but in the chambers the product was heat-insulated. The latent heat of evaporation of ice is about 700 calories per gramme between -25°C and -30°C . This is a theoretical figure, and Greaves and Adair obtained a 'practical' figure of about 900 calories per gramme from a freeze-drying apparatus. Each gramme of water requires this amount of heat for evaporation and the rate at which the heat is supplied determines the speed of drying. There are obviously limits to the rate at which the heat can be applied. One of them is imposed by the safe, limiting temperature of the drying material, which not only must not thaw but should not even get within twenty or so degrees of thawing. Another is the capacity of a mechanically-refrigerated condenser for dealing with large amounts of relatively hot water vapour.

The heating problem was subsequently overcome by winding resistance wire round the tins in which the individual containers were placed and passing an electric current through the wire. A recording thermocouple or resistance thermometer embedded in the frozen contents of one of the containers enabled the pro-

gress of the heating to be followed and controlled. Such control can now be made automatic by allowing the actual drying temperature to influence the heating on a 'feed-back' principle.

The introduction of mechanically-refrigerated condensers depended upon the development of reliable compressors. Such condensers usually operate at about -40°C , which corresponds to an equilibrium vapour pressure of 0.1 millimetre of mercury. This pressure is well within the range of modern oil-sealed single-stage rotary vacuum pumps although they must be of large capacity since, at this pressure, 1 gramme of water occupies a volume of 9,500 litres. When the condenser temperature is -78°C , the dry product has a water content of about 0.1 per cent. However, with a condenser temperature of only -40°C the residual moisture may be as high as 4 per cent. It is often necessary, therefore, to give such materials a secondary drying over a chemical desiccant such as phosphorus pentoxide to reduce the water content to an acceptable amount.

During the war years very large amounts of dried human serum and plasma were required for transfusion purposes, and this requirement, closely followed by plans for freeze-drying penicillin, led to rapid progress. In Great Britain, in the three years 1943-5, the plant designed by R. I. N. Greaves supplied 318,700 bottles each containing the dry equivalent of 400 millilitres of blood products. A new prefreezing method was developed in which the transfusion bottles were spun on their vertical axes at high speed in an air-draught at -18°C . The liquid froze round the inside periphery of the bottle, so presenting a large surface area from which sublimation took place. The bottles of frozen plasma were then rapidly transferred to the drying chamber. Subsequently Greaves incorporated a centrifuge unit in the vacuum chamber. Frothing was avoided, the liquid froze by evaporation, and the freezing process thus became the first stage of the drying process itself. Centrifuging not only completely suppresses the foaming of the liquid during the early stages of evacuation of the drying chamber and condenser but also distributes the material in a wedge in the container (Inset 15).

The choice of freeze-drying equipment at the present time depends on the scale, frequency, and conditions of use, as well as on the particular application which is in question. The simplest method is still, of course, to use a standard laboratory desiccator with phosphorus pentoxide as the desiccant and to reduce the pressure slowly over the liquid material so that 'degassing' is controlled. Finally it will snap-freeze, and pumping, with a small rotary vacuum pump connected to the desiccator with large bore rubber tubing, may be continued until the product is dry.

More elaborate, more reliable, but, alas, more expensive, apparatus is available, which in this country incorporates the essential features of Greaves's large scale plasma-drying plant, such as a mechanically-refrigerated condenser operating at a temperature of at least -40°C , centrifugal spin-freezing, and controlled heat input to the drying material. Such an apparatus is illustrated in Inset 17. The centrifuge head is housed in the primary drying chamber which has a thermostatically-controlled radiant heater in the wall. The chamber is connected by a very wide metal tube to the refrigerated condenser chamber. The vacuum pump connexion is taken up into the centre of the cold coil so that all the water-vapour is condensed without risk of contaminating the pump oil.

As a final example, we may take a British, commercially produced, blood plasma freeze-drying unit with a capacity of 500 litres per week. Such a unit is shown diagrammatically in Figure 1. The primary drying units (1) have the condenser (cooled by circulating alcohol at -40°C) in the same chamber as the bottles of frozen plasma. At the end of the primary drying cycle when the water content of the plasma has been reduced to about 3 per cent the bottles are transferred to secondary vacuum driers (11) where the water content is further reduced to less than 1 per cent. Heat input to the drying plasma in the primary drying cycle is thermostatically controlled and a safety switch is incorporated which cuts out the heating circuit if the vacuum in the chamber is not maintained. Recording thermometers and pressure gauges are used to follow the whole processing cycle.

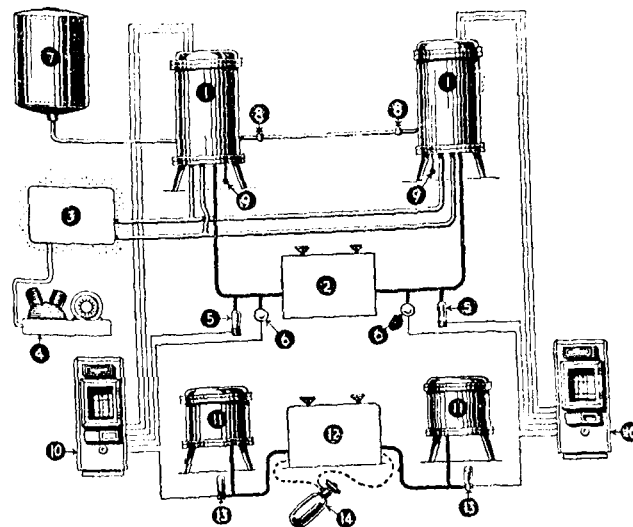


Fig. 1. Diagrammatic flow-sheet of an Edwards plasma freeze-drying unit for 500 litres per week: (1) primary desiccators and (2) the pumping unit for them, (3) refrigerated tank from which cold brine (or alcohol) is circulated to cool the condenser coils within the primary desiccators, (4) low-temperature mechanical refrigerator, (5) and (13) measuring heads for vacuum gauges, (6) vacuum switches to protect plasma in the event of failure of refrigeration or vacuum, (7) and (8) hot-water storage tanks and valves for melting ice off condenser coils after drying is completed, (9) water-drain valves for removing melted ice and hot de-frosting water from the desiccators, (10) electrical recording instruments for vacuum measurement and control, (11) secondary drying desiccators and (12) the pumping unit for them, (14) dry nitrogen or other inert gas for filling the dried bottles. A photograph of this unit is reproduced as Inset 19.

The secondary driers employ a chemical desiccant and, when this final drying cycle is completed, the bottles are filled with pure, dry nitrogen before sealing. The primary drying condensers are

rapidly defrosted by flooding with hot water from a storage tank (7), a procedure which ensures their maximum utilization. A photograph of this equipment is reproduced as Inset 19.

APPLICATIONS IN BIOLOGY AND MEDICINE

The development of freeze-drying as a technique has been linked closely, as has been seen, with requirements for the preservation of human blood sera and plasma, and the first clinical application was, in fact, the production by Flosdorf of convalescent human sera for injection. The dried sera, from cases of measles, scarlet fever, chicken pox, and mumps were distributed by the Philadelphia Serum Exchange and were used in the prevention and control of epidemics. This work gave place to the enormous plasma-drying programmes of the war years when in the United States alone production reached a level of 100,000 units per week. Most of the essential properties of the plasma are preserved in the freeze-dried material for at least five years; after this time the prothrombin activity drops progressively, but the plasma is otherwise satisfactory for at least ten years.

Antibiotics

The large-scale production of penicillin became an urgent necessity in 1943 and, at that time, the experience with plant designed for dry blood-plasma production was available to meet the new problems. Penicillin is now isolated in crystalline form, but the scale of the original freeze-drying in small individual containers, each containing only 1 or 2 millilitres, made it one of the largest industrial applications of the process to pharmaceutical products. With such small quantities in each vial, spin-freezing to distribute the material in the container was not necessary and the freezing was usually carried out by standing metal trays of vials on plain metal shelves with a refrigerated coil brazed or welded to the undersurface. The trays of vials with their frozen contents were then transferred to similar shelves in the vacuum chambers. The heat required for sublimation of the ice was supplied to the shelves either by circulation

of hot water through them or by electrical heaters attached to the underside.

Streptomycin products are obtained initially as aqueous solutions containing about 40 per cent of solids, and these are more conveniently treated in stainless-steel trays filled to a depth of about 2 centimetres. The trays are filled *in situ* on the metal shelves of the drying chamber, and the solution is frozen by circulating refrigerant through the shelf-coils. When the temperature has fallen to -30°C the pressure in the vacuum chamber is rapidly reduced. When the equilibrium pressure is reached (0.2 millimetre of mercury for -30°C), circulation of refrigerant to the shelves is stopped and the electric heaters are switched on. The heat input is adjusted to give an initial drying temperature of -28°C , but at the end of the drying cycle, to remove the last traces of water, the temperature of the almost-dry solid is allowed to rise to 40°C .

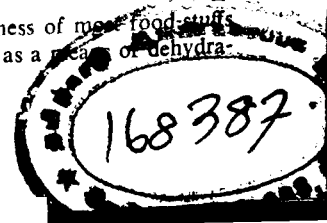
Food Products

Freeze-drying is an expensive process, and, for freeze-dried food to be economic, the final product must be superior to that obtained either by quick-freezing alone or by dehydration at a higher temperature. So far as the freezing part of the freeze-drying process is concerned, the material starts on the same level as quick-frozen food. The advantages of a subsequent dehydration may be not in superior quality but in low bulk, ease of handling, and storage at higher temperatures.

In general, liquids such as milk, orange juice, and soup will tend to give more acceptable products than fruit and vegetable tissues, since the soluble constituents of the latter tend to come out on soaking and the tissues do not regain their original firmness. Flosdorf records the application of freeze-drying to the preservation of orange juice, meat, oysters, clams, fish fillets, goat's milk, coffee and tea extracts, peas, carrots, beets, and soups. Dr R. Gane, however, concludes a recent review of the subject:

The high water content and relative cheapness of most food-stuffs preclude the economic use of freeze-drying as a means of dehydration.

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tion. . . . It may be that the process could better be used as one stage in the dehydration process, either as a preliminary treatment to render tissue porous so that subsequent drying by heated air could proceed rapidly, or, alternatively, as a final stage to achieve the required water content safely.*

There is, however, one special food, human milk, for which preservation by freeze-drying has been practised with great success. In Holland, the Netherlands Red Cross collects surplus milk from voluntary donors, pools, pasteurizes, and freeze-dries it in units of 100 millilitres in apparatus closely similar to that used for freeze-drying blood plasma. The product is supplied on a medical prescription only and in five years 100,000 units have been distributed.

Micro-organisms

Unless methods of preservation are available, the maintenance of virus, bacterial, and mould collections at, for example, the National Collection of Type Cultures, necessitates the continued passage of the micro-organisms *in vitro* or *in vivo* with all that is thus entailed in labour and expense. Preservation by freeze-drying offers an alternative. It is, of course, an essential proviso that the desiccates so obtained should retain quantitatively the characters of the original organisms.

So far as viruses are concerned, simple freezing and maintenance at -25°C or less frequently suffices for their preservation in infected fluids, organs, or tissues, and such materials may also be straightforwardly dried from the frozen state, conditions which viruses will usually survive. Large quantities of living virus vaccines are now being produced to immunize cattle in Africa against rinderpest, fowls against Newcastle disease and plague, and man against yellow fever. It is essential that these vaccines should not lose potency so rapidly that their employment in the field becomes difficult, and should not be so expensive that their use is thereby restricted. Dr R. Daubney has said of rinderpest:

*In *Biological Applications of Freezing and Drying*, edited by R. J. C. Harris. Academic Press, 1954.

At once it became possible and practicable to plan for the complete eradication of the disease – by mass immunization – from vast areas of Africa, where it had remained enzootic since the closing decade of the nineteenth century; and in very large measure these new possibilities had been opened up by the development of practical apparatus for the freeze-drying of tissues containing the virus. The new method enabled us to give life-long protection to millions of native cattle of such low economic value that they did not warrant the expense of immunization by the older methods.*

However, once viruses are separated from the tissues and 'purified', they become increasingly difficult to preserve even in frozen suspension. It then becomes necessary to include protective agents in the suspending media. Such materials as proteins, peptones, and carbohydrates have been found to protect viruses in this way, but the mode of action of such substances is unknown. Moreover, media which protect viruses against freezing and thawing may not confer equal protection against freeze-drying. On the other hand, labile viruses have been successfully freeze-dried in such unpromising media as saline, buffers, or water, by lowering the temperature of the frozen suspension and prolonging the drying cycle.

Many bacteria have some degree of resistance to drying, even at room temperatures and pressures, but the very careful work of Dr R. M. Fry and Dr R. I. N. Greaves at Cambridge has shown that the nature of the medium in which bacteria are dried has a very great effect on the survival rate and is possibly the most important single factor in the whole drying process. Many other factors in the freeze-drying and storage procedures were investigated, such as the conditions of growth and age of the culture, the cell concentration of the bacterial suspension, the degree of vacuum and the drying temperature, the atmosphere of storage, the temperature of storage, residual moisture, and water absorption during storage.

The problem has two aspects. Some organisms may not survive the drying procedure and others which may survive drying fairly well may not survive for long in the dried state. So far as

*In *Freezing and Drying*. London, Institute of Biology, 1951.

the former are concerned, there can be no doubt that the composition of the suspending medium is all important. Colloid suspensions seem to be the best, but some crystalline substances, such as glucose, also appear to protect, and their action may be related initially to the residual water content of the dried material and later to possible redistribution of this water during storage. So far as storage is concerned, there can be no doubt that oxygen is harmful, and sealing in evacuated containers is the best method.

Tissues for Transplantation

Whereas, until a few years ago, research in the transplantation of tissues had been of primary interest to a few biologists, today tissue grafts, and the problems of their preservation and behaviour in the host, are of direct interest to surgeons. Skin grafts are only permanently successful when the skin is taken from another area of the patient's own body – an autograft. Skin from another individual (a homograft) may be accepted for a time, but, sooner or later, the graft is rejected. However, for some tissues such as bone, cartilage, and blood vessels, grafts obtained from another individual, either *post mortem* or in the operating theatre, may give a perfectly satisfactory repair.

'Tissue-banks' have been formed where such tissue 'spare parts' may be stored in assorted lengths and sizes ready for immediate use. Bone and cartilage grafts do not appear to be incorporated as such into the recipient. They act, instead, as a framework within which new bone or cartilage is formed and, ultimately, the framework itself may disappear much as the scaffolding is removed from a newly-completed building. So long as these grafts are not infected, therefore, it is of no consequence whether they are 'alive' or 'dead', and storage presents little difficulty. Cartilage grafts are often stored in a preservative, antiseptic solution at ordinary refrigerator temperatures. Bone grafts may be banked at lower temperatures of -20° to -30° C ('deep-freeze'). Other tissues are not so readily preserved, and it is for these that the methods of freezing and freeze-drying have been investigated.

Nerve injuries may, for example, be successfully repaired by autografts, but peripheral nerve homografts in man have always failed. Claims have been made, however, that frozen-dried homografts could be used to repair short gaps in peripheral nerves in monkeys, cats, and rats. The extension of such studies to man does not appear to have been attempted.

Blood vessel homografts are now being used on an ever-increasing scale. As with cartilage and bone, such grafts do not have to be 'alive' to produce a functional repair. Most 'banks' at the present time freeze the grafts in a solid carbon dioxide bath (at -78° C) and store them at this temperature. However, it is possible to preserve arterial segments by freeze-drying, and Dr Charles Hufnagel, of Georgetown University Medical Center, Washington, has stated that the results obtained with fresh, frozen, or freeze-dried homografts are practically indistinguishable. He has also employed freeze-dried *heterografts* (i.e. from other species) from a calf and from a young pig with successful results.

The Tissue Bank of the Naval Medical School at Bethesda, Maryland, freeze-dries and stores bone, blood vessels and skin (although homograft skin does not form a permanent graft) and claims that preservation by freeze-drying has the great advantages over simple freezing of simplicity and ease of storage and transport, and of increased storage time, which allows tissue reserves to be accumulated. Bacteria and viruses withstand freeze-drying, but there is, as yet, no evidence that mammalian cells can survive dehydration to such a degree. Where a graft depends for its value upon the functioning of the cells, as for example in the grafting of thyroid tissue into a thyroid-deficient individual, then the preservation of such a graft presents problems which freeze-drying has yet to solve. It is nevertheless amazing that so much effective surgical use can be made today of dead bone, cartilage, and artery.

Tissue Dehydration and Fixation

Histologists and cytologists who study the morphology of cells, tissues, and organs are concerned with techniques for

preservation which will result in preparations approximating as closely as possible to the living state. Most of the chemical methods which have been used for fixation, e.g. formol-saline, Bouin's solutions and their like, have disadvantages in that they distort, dissolve, 'denature', or attack chemically some of the constituents of the cells and tissues. Many of these difficulties are overcome by freeze-drying the tissues. Even rapidly-diffusing substances within cells are retained in this way, and, if care is taken in the subsequent embedding and staining, the degree of preservation achieved is far greater than by any other method. One serious artefact that may be introduced is the formation of ice-crystals, which after drying will appear as vacuoles in the tissues. The size of these vacuoles will depend to a large extent on the rate of initial freezing of the specimen. A very low temperature liquid freezing bath (usually isopentane or propane cooled to liquid air temperatures) and thin tissue sections (a few tenths of a millimetre) combine to give very rapid freezing and reduced ice-crystal artefact. It is not convenient, however, to dry the specimens at this temperature since the rate of drying would be very small. The specimens are transferred to the drying head of the tissue drier unit (Figure 2), which is cooled to -78°C in large Thermos flasks containing a bath of solid car-

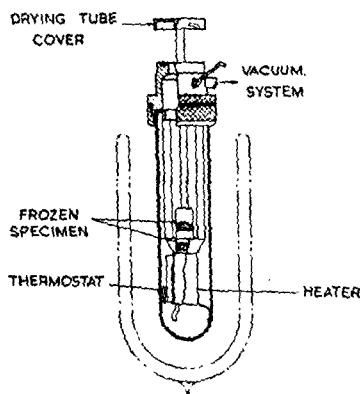


Fig. 2. Diagram of tissue-dryer drying tube; see Inset 18,

bon dioxide in acetone or alcohol. The outer glass wall of the head thus acts as the condenser and receives the water vapour sublimed from the specimens. A small heater is incorporated in the drying head so that the temperature of the specimens may be controlled at the required figure (usually -30° to -40°C). When the tissues are quite dry the flask is removed and the ice revaporized from the walls and absorbed in a chemical desiccant. A photograph of this unit is reproduced as Inset 18.

Freeze-drying has also been successfully applied to the preparation of specimens for electron microscopy. Conventional air-drying methods tend to produce flattened objects as a result of the action of surface tension forces during the process. Professor Robley Williams, of the University of California, Berkeley, has devised a new technique for freeze-drying in which extremely small droplets of specimen material are frozen rapidly on impinging upon a very cold copper surface. The ice may be quickly sublimed *in vacuo* and the results which he has obtained in the retention of three-dimensional structure for bacteria, fibres, and viruses show that the method is a great improvement.

FURTHER READING

- Greaves, R. I. N. *The Preservation of Proteins by Drying with Special Reference to the Production of Dried Human Serum and Plasma for Transfusion*. London, Medical Research Council, Special Report Series No. 258, 1946.
- Flaschdorf, E. W. *Freeze-drying - Drying by Sublimation*. New York, Reinhold, 1949.
- Freezing and Drying*. A symposium report, edited by R. J. C. Harris. London, Institute of Biology, 1951.
- Preservation and Transplantation of Normal Tissues*. Ciba Foundation Report. London, J. & A. Churchill, 1954.
- A Discussion on the Maintenance of Cultures by Freeze-drying*. S. T. Cowan, for British Commonwealth of Nations Scientific Liaison Offices. London, H.M.S.O., 1954.
- Biological Applications of Freezing and Drying*. Edited by R. J. C. Harris. New York, Academic Press, 1954.

RESEARCH REPORT

A. W. HASLETT

COLONY FORMATION IN ALGAE

THE control of growth and reproduction in colony-forming species of single-celled organisms presents problems which are of interest to others besides the specialist. They have been studied in the green alga *Pediastrum duplex* by J. G. Moner, working in the Department of Biology, Princeton University. He has shown that, under suitable conditions of culture, there are two distinct phases of development – one in which the colonies grow, the other the phase of 'swarming' in which new colonies are produced from them. The transition from the first phase to the second is probably brought about by a substance secreted by the organisms.

The *Pediastrum* used by Moner came in the first place from Malham, and was provided by Dr E. G. Pringsheim of the Department of Botany, Cambridge University. Quoting more or less directly from Moner's description, the colonies are commonly found in fresh water and are disk-shaped. The cells which compose them are arranged in a single layer, and the outside ones differ usually from the rest in having one or more prongs or processes which extend radially outwards. The number of cells in a colony is, in general, such as would result from successive doublings starting from one; the common range is from 8 to 64. The formation of colonies depends on the formation of motile cells, zoospores, those from a single cell of the original colony becoming the new one. These motile cells are formed by successive divisions of the cell nucleus, followed by progressive cleavage of that part of the mother cell which contains the chlorophyll necessary for photosynthesis. The cells acquire two flagella each. They are discharged through a crescent-shaped

slit in the cell wall of the mother cell, and are enclosed in a thin, transparent sac. At first they form an irregularly shaped mass, within which the individual cells move actively. After three or four minutes, they slow down and form a flat plate of cells. Movement then ceases, and prong formation begins; this is completed in a matter of minutes. The colony, now established, grows by cleavage of its cells.

The culture as received from Cambridge contained only the one strain of alga, but was not necessarily free from bacteria. Further cultures were grown under sterile conditions in a standard solution of mineral nutrients, to which 10 per cent of soil extract was added. The initial observation – that the phases of growth and colony formation could be separated – came about from the wish to obtain many swarming colonies quickly. With this object relatively large additions of culture were made to fresh culture medium (5 ml into 50 ml). Under these conditions, it was noticed that swarming occurred at a definite time after inoculation and seemed to last for only a few days. In one quantitative experiment there was no production of colonies up to 173 hours, but there was then a sudden burst of activity; this began at 197 hours, lasted for 78 hours, and thereafter levelled off.

The next move was to replace the new medium, either at once or after 2 or 4 days, by 'aged medium' obtained from a 19-day-old culture from which the colonies had been removed. The effect was, in all cases, to accelerate colony production compared with a control culture in new medium. Colonies began to be produced, at the latest, after 73 hours. A second effect was connected with the length of time during which the culture had been left to grow in fresh medium; the longer this time, the greater was the level of colony production after transfer to 'aged medium'. Thirdly, the size of the colonies was reduced, compared with control cultures.

It was supposed therefore that a change took place in the medium which affected both the timing and level of colony production, and also the size of the colonies. The medium changes during culture from being slightly acid to slightly alkali-

line, and this was thought to be one possibility. An experiment was therefore performed in which fresh medium was adjusted to the same degree of alkalinity as that in the 'aged medium'. The time of colony production was not affected. Other experiments were done to test the effect of heat on any substance that might have been released into the medium by the organisms previously grown in it. 'Aged medium' was heated for 30 minutes under pressure at a temperature of 121° C. So far from its activity being destroyed, there was a 3 times greater production of colonies in medium so treated than in untreated 'aged medium'. Previous research on other species of algae had shown them to produce inhibitors. It is therefore suggested that *Pediastrum* produces both stimulating and inhibitory substances, and that the former are more resistant to heat. The conclusion that substances of both types are produced is reminiscent of the present situation in research on plant hormones, and indeed in relation to the control of physiological processes in general.

Moner, J. G. *The Biological Bulletin*, 107, 236 (1954).

ENERGY OF MUSCULAR CONTRACTION

For several years past, the immediate source of the energy used in the contraction of muscle has been widely assumed to be the breakdown of adenosine triphosphate. According to a 1950 text-book: 'Whatever view is finally adopted to account for the initial step, it is clear that the breakdown of adenosine triphosphate is the fundamental chemical process which supplies the energy'. The evidence, though considerable, was indirect; it was difficult to reconcile on some points with the physical evidence obtained by Professor A. V. Hill, who in 1949 called for a straightforward demonstration of the chemical changes which accompany a single muscular twitch. Evidence has lately been published from three different laboratories, one of them working independently of the other two, which suggests that 'muscle can in fact do work under well-defined conditions without the decomposition of an energetically equivalent amount of adenosine triphosphate. . . .'

The previous evidence was of the kind described in lawcourts as circumstantial. Processes such as respiration and the breakdown of glycogen in muscles, which indirectly support muscular activity, had been shown to do so through the synthesis of adenosine triphosphate. In 1939, myosin, thought to be the contractile element of muscle, had been found to be associated with an enzyme by which adenosine triphosphate is broken down. More spectacularly, Professor A. Szent-Gyorgyi had, in 1946, reported that 'reconstituted' fibres could be prepared from actomyosin, extracted from muscle, and that these fibres could be induced to contract by adenosine triphosphate, also extracted from muscle, although they could not mimic the work done by muscle during contraction. It may still therefore be doubted whether adenosine triphosphate should be removed entirely from the story.

The first of the two new reports comes jointly from Professor A. Fleckenstein and Dr J. Janke of the Pharmacological Institute, Heidelberg University, and Dr R. E. Davies and Professor H. A. Krebs of the Medical Research Council Unit for Research in Cell Metabolism at the University of Sheffield. The crucial experiments were carried out on slow-responding frog's muscle at a temperature of 0° C. Pairs of corresponding muscles from the same animal were respectively stimulated and kept as controls. By various procedures, including paper chromatography, estimates were made of the quantities present in each not only of adenosine triphosphate but also of other possibly relevant substances. These included creatine phosphate (from which adenosine triphosphate might be regenerated) and inorganic phosphate. When the stimulus to contraction was chemical, there was indeed some reduction in either adenosine triphosphate and creatine phosphate, or in creatine phosphate alone, according to the stimulating substance. But with electrical stimulation there was no reduction in either, although there was a liberation of inorganic phosphate in just sufficient quantities to supply the energy needed for contraction. It follows, these authors conclude, that there is a source of energy in living muscle which either (like creatine phosphate) can synthesize

adenosine triphosphate rapidly, or which 'is closer to the process of contraction than the breakdown of adenosine triphosphate'.

The second report is from Dr W. F. H. M. Mommaerts of the Department of Biochemistry, Western Reserve University School of Medicine, Cleveland, Ohio. His experiments were done on pairs of leg muscles of turtles – one, again, being stimulated, and the other used as a control. At a chosen moment, early or late in contraction, the muscles were immersed suddenly in liquid propane, cooled to a temperature of -185°C . Contraction was at once stopped, and rapid cooling of the muscle was confirmed by temperature measurements made inside the muscle. Subsequent chemical procedures were designed to look for probable breakdown products of adenosine triphosphate or creatine phosphate, as opposed to changes in the quantities of these substances present in the muscles. No evidence of such breakdown products was found; and a new 'revolution in muscle physiology' (a title used 22 years ago by Professor Hill) is stated to be clearly discernible.

Fleckenstein, A., Janke, J., Davies, R. E., and Krebs, H. A. *Nature*, **174**, 1081 (1954).

Mommaerts, W. F. H. M. *Nature*, **174**, 1083 (1954).

INTERNATIONAL GEOPHYSICAL YEAR

The International Geophysical Year 1957–8 is best regarded – as in fact it originated – as a repetition and extension of the International Polar Year of 1932–3, just as this latter was a repetition and extension of the first polar year of 1882–3. Compared with normal conditions of observation, the most important effect of the last polar year was that various types of observation, which, in the main, had been confined before to temperate or tropical conditions, were extended to the Arctic fringe. The outstanding result was the picture which emerged of the connexion between disturbances on the sun, the effects of these on ultra-violet radiation and charged particles reaching the earth's upper atmosphere, observations of electron-density in the iono-

sphere, the propagation of radio waves over long distances, magnetic disturbances, and displays of aurora. The mere recital of this list is sufficient indication that, to attain their full value, observations made in polar regions require to be considered as part of a world programme. There are also many new elements in the situation. Among them are a more hopeful attitude to the study of the general circulation of the atmosphere; interest in the present climatic fluctuation, especially in the northern hemisphere; greater knowledge of ice-flow and a desire in consequence to make a more extended study of the ice-sheets of Greenland and Antarctica than has yet been possible; and many new methods of observation, including the use of rockets to make direct measurements of conditions in the upper atmosphere. The techniques of gravity surveys and of seismic observations, for example of the depth of ice sheets, have also been much extended; and the development both of air transport and of mechanized ground transport under polar conditions has made it possible to envisage the use of instrumental equipment which could not before have been considered.

A meeting of the Special Committee for the International Geophysical Year (C.S.A.G.I.), held in Rome during last autumn, made it clear that a substantial effort can be counted on from the United States, that support is to be expected also from the U.S.S.R. – as clearly is necessary for success – and that many of the smaller countries are anxious to contribute effectively to the arrangements. So far, 35 countries have agreed to take part.

Because of the world-wide character of the intended programme, it is proposed that special observations should be made during selected days and periods. The 'year' will extend from July 1957 to December 1958. There will be two 'world days', already provisionally designated, in each month, one at new moon, the other at about quarter moon, with the exact day adjusted to coincide with major meteor showers. There are also to be special 'world intervals', periods in which unusual solar activity is expected, with a system of broadcast and other warnings to bring the observers to the alert. Thirdly, there are to be

'world meteorological intervals' – six periods of 10 consecutive days in each quarter at solstices and equinoxes, which will include the regular world days of the same month. As well as the Antarctic and Arctic, there is to be a concentration of effort geographically; the other selected regions will be the equatorial belt, which is of special magnetic interest, and three meridional lines from North to South Pole.

Plans for rocket soundings of the upper atmosphere have been put forward by the United States and by France. For research on the ionosphere, 86 stations in the northern hemisphere and 30 in the southern have been listed as likely to participate, and the creation of 24 more stations is recommended. For the observation of solar activity, a continuous patrol by a world network of stations is proposed, and recommendations about instruments and procedure have been made in detail. A thoroughly organized cosmic-ray programme will, it is suggested, help in conjunction with other data in arriving at physical concepts of the electro-magnetic system of the sun, earth, and interplanetary space; it is hoped that some 70 stations, 34 already existing, will participate. Again, standard measuring instruments are proposed. Other programmes which have been planned include a series of observations related to latitudes and longitudes. This will serve many objects: the improvement of time determinations, the study of irregularities in the earth's rotation, star catalogues, redetermination of the relative positions of the continents, and knowledge of the practical propagation of radio waves. Widely spread as the whole programme must appear, it seems likely that a large part of it will be executed. Many who came to Rome doubtful were convinced by the detailed discussions which then took place; and the extent of support already assured from the United States may, in effect, compel other governments to make proportionate efforts, especially in the more geographical parts of the programme.

COMPARISONS OF FREQUENCY AND TIME

The situation has existed for many years that standards of radio-frequency, based on the mechanical vibration of quartz

crystals, can be compared in the laboratory with a higher standard of precision than that with which the unit of astronomical time can be predicted. Recent experiments, jointly reported by British and American radio physicists, show this to be true also of frequency comparisons made by radio transmission across the Atlantic. A new order of accuracy in the comparison of time-intervals on a world-wide basis is thus made possible, and the need underlined for a laboratory standard of time independent of the rotation of the earth.

The weakness of the rotating earth as a time standard is that there is both a slow increase in the length of the day, caused by the braking effect of the tides, and, superimposed on this, larger, short-term variations attributed to movements of a few feet in the earth's crust, and also seasonal changes. The evidence is in part astronomical and in part from comparisons between astronomical time and that kept by batteries of crystal-controlled clocks. The astronomical evidence is obtained by comparing the rate of rotation of the earth with the movement of the moon round the earth, that of the innermost of four large satellites of Jupiter round that planet, and the movement of both the earth and Mercury round the sun. Since the rotation of the earth is taken as the standard of time, the comparison is in effect between the tendency of these other time-keepers to gain or lose at the same rate, judged by the earth's rotation. Both the annual slow increase, estimated in this way, and the seasonal changes, estimated from crystal-controlled clocks, are of the order of 1 part in 10^8 , and this is the accuracy with which the unit of astronomical time is commonly stated to be predictable. There is, however, some evidence that the effects of short-term changes, unpredictable and continuing over a number of years, may be greater than this.

Radio frequencies can be compared in the laboratory with a precision of 100 times as great (1 part in 10^{10}). If measurements are continued for a month, the attainable stability falls to a few parts in 10^9 , and during longer periods of time there tends to be a drift in the frequency of the crystals. Quartz crystals would, for this reason, be unsuitable for use as standards.

The new precision attained in comparisons by broadcast signal has been reported jointly by J. A. Pierce of the Cruft Laboratory, Harvard University, H. T. Mitchell of the Radio Experimental and Development Laboratory, British Post Office, and Dr L. Essen of the National Physical Laboratory, Teddington. It has been made possible by the introduction of an additional frequency as an experiment when the broadcasting of standard frequencies for reference and comparison was resumed in 1950. The official frequencies are 2.5, 5, 10, 15, 20, and 25 megacycles per second. These are reflected for the most part in the F_2 region of the ionosphere, which varies markedly in height (from about 200 to 1,000 kilometres). The rate of variation in height, and therefore in path-length from transmitter to receiver, is great enough to introduce significant changes in the received frequency. For this reason the accuracy of comparison at these frequencies is limited to about 2 parts in 10^7 .

It was because of this limitation that experimental transmissions were introduced at a frequency of 60 kilocycles per second. At this much lower frequency, reflection is in the D region of the ionosphere which remains comparatively stable in height at around 50 to 65 kilometres. Transmissions are from the Post Office Radio Station at Rugby, and are at low power (10 kilowatts). Despite this they have been received and measured at Harvard with a precision of 1 part in 10^9 ; this is the same order of accuracy as that attained in more or less local measurements at Teddington. The authors comment that this result is clearly of significance in problems of frequency control, international frequency and time standardization, and also in relation to certain types of navigational aid. The possibility of making such measurements absolute instead of comparative depends on the development of laboratory standard of time, based possibly on the natural frequency of vibration of an atom in a molecule. Work with this object was reported by the U.S. National Bureau of Standards in 1949 and is still proceeding.

Pierce, J. A., Mitchell, H. T., and Essen, L. *Nature*, 174, 922 (1954).

SEA-BED HISTORY

Two examples have been published of the use of the carbon-14 method of dating to elucidate the past history of relatively shallow areas of sea-bed. They are included in a summary of results obtained with an apparatus recently developed by Professor H. de Vries and G. W. Barendsen, of the Physical Laboratory of the State University of Groningen in Holland. There is a departure in method compared with the original technique of measurement, as developed by Professor W. F. Libby of Chicago University. Whereas in the Chicago apparatus the radioactivity of samples is measured with the carbon in solid form, in the Groningen apparatus the counts of radioactivity are made from gaseous carbon dioxide.

The first of the sea-bed problems is that of the past history of the Gulf of Paria which lies between the mainland of South America and Trinidad. An arm of the river Orinoco discharges into the gulf on its southern side, and from geological evidence it was expected that this would be found to have broken into the gulf in more or less recent times. By this 'catastrophe', shell-beds containing marine species were killed by the inrush of fresh water. Sample shells were therefore obtained from eight sites round the edge of the gulf, two samples being included from different depths at one site. Those from an appreciable depth (50 to 150 centimetres) below the sea bed were found to be of older age than the others. Another two were expected to be of recent origin and were found to be. The remaining four samples gave ages which were mutually consistent and averaged about 800 years.

The second problem is to determine the rate of lowering of the Dutch coast relative to sea-level. An extensive programme is being carried out with this object on behalf of a committee which is concerned with the possible closure of the estuaries of south-west Holland. Up to now, about forty samples of peat and shells have been dated, and dating of the peat is being carried out also by the method of pollen analysis. Details of the geological argument are not included in the present summary;

but the broad conclusion is given that the rate of sinking of the bottom was about 35 centimetres per century some 7,000 years ago, and is about 10 centimetres per second at the present time.

de Vries, H.L., and Barendsen, G. W. *Nature*, **174**, 1138 (1954).

SOLAR ENERGY

With nearly a million square miles of arid land in the U.S.S.R., one tenth of which is sandy desert, the use of solar energy for heating, distillation, and cooling has been seriously examined. An account of this work was given by Professor V. A. Baum, Director of the Heliochemical Laboratory at the G. M. Krzhizhansky Power Institute, Tashkent, at a symposium on solar energy and wind power which was held recently at New Delhi under the joint auspices of Unesco and the National Institute of Sciences of India. The following notes are from a report issued by Unesco. It should be remembered that the work described was done in a dry, continental climate in about the latitude of Rome.

Solar heating units have been developed which use paraboloid reflectors 10 metres in diameter that can be turned to face the sun all day, and which produce 100 pounds (60 kilogrammes) of steam per hour at a pressure of 100 pounds per square inch (7 kilogrammes per square centimetre). The efficiency of utilization of the mirrors is about 70 per cent. Such units have been used for the operation of canneries, refrigerators, and for laboratory heating. Another application is in the distillation of fresh water from salt for livestock on remote pastures; 75,000 tons of distilled water have been produced by one still in a year. This has proved the cheapest method of supply in the conditions prevailing; but the emphasis is, in general, more on the social importance of using solar energy than on economic considerations.

Various other types of unit have been built or are being developed. An industrial heater produces 18 tons of steam per hour, or 33,000 tons per year, the latter figure being equivalent

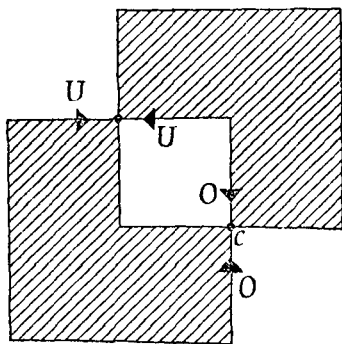
to an average of some 5 hours' operation at maximum output per day. Two sizes of domestic unit have been developed. The smaller one has an aluminium mirror about 1.2 metres in diameter; the larger one has a surface area of about 12 square metres. Development work is proceeding on a steam generator which can be used both as a heating plant in winter and for cooling in summer; this is intended for cinemas, hospitals, and larger houses. The problem of electricity generation has not, however, been solved, because of the difficulty of storing the energy collected, as would be necessary to cope with fluctuations in sunshine, time of day, and seasonal changes. In spite of this Professor Baum envisages a great expansion in utilization.

CORRESPONDENCE

CELTIC PATTERNS AND TOPOLOGY

THE topological theorem proved by Mr Thurston in his interesting article on Celtic weaves (*Science News* 33) can be proved more shortly as follows.

Suppose the pieces into which the pattern curves divide the plane to be coloured black and white, so that a black and a white piece meet along each arc. (Assume for the moment that this can be done.) At each crossing ('node'), c , one of the two strands has *black on the left* as it approaches c in either direction. Let this strand go over, the other under, at c . Each arc from node to node goes over (O) at one end, under (U) at the other, since the left side going towards one end is the right going towards the other. Therefore over and under alternate along each loop, and all is proved.



The 'black-and-white' theorem here used is used also by Mr Thurston when he says that every curve (even if self-intersecting) has an 'inside' (his Figure 15): the 'inside' is just the black regions. He assumes the theorem only for a single loop, but the

proof to which he refers based on cutting up into curves with no nodes (p. 56) works just as well in the general case. The black-and-white theorem can also be proved directly by colouring a region black if you have to cross the pattern-curves an odd number of times in walking out of it to the distant part of the plane. It is not hard to see that, for a given region, the number of crossings is always odd, or always even.

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SOME BOOKS RECEIVED

THE SCIENTIFIC REVOLUTION by A. R. Hall (London, Longmans, Green & Co., 1954), pp. 390, 21s.

Writings about the formative period of science have suffered from the weakness that those whose approach has been from the side of science have for the most part either been ignorant that problems of origins exist or have recognized only one solution, while general historians have only newly discovered science. Mr Hall's 'character study' may be in some danger of being dismissed as a rather lengthy prolegomenon to a statement of how little is really known. In fact, it is probably as good a general review as has yet been written, and provides also a much-needed backcloth on which further 'case studies' can be painted in – by the author among others, as one may hope.

THE PHYSIOLOGY OF INSECT METAMORPHOSIS by V. B. Wigglesworth, F.R.S. (Cambridge University Press, 1954), pp. 152, 12s 6d.

This is the first of a new series of 'Cambridge monographs on experimental biology' which are to be authoritative, quickly published, and of about 40,000 words length. Professor Wigglesworth's authority is beyond question; and there is interest in his argument that insect metamorphosis is to be regarded merely as an especially striking example of the occurrence of differences in form between different individuals of a species, and as an introduction, too, to differentiation. But he would probably have done better to have given more complete rein to his own work, confining his main chapters to the insect – the Hemipteron, *Rhodnius prolixus* – on which he made his own discoveries about hormonal control, and thence worked outwards, through metamorphosis in other insects, to the argument already mentioned.

THE GENETICS OF PARAMECIUM AURELIA by G. H. Beale (Cambridge University Press, 1954), pp. 179, 12s 6d.

In *Science News* 34 (p. 80) Professor Wyburn referred briefly to work on a single-celled organism, *Paramecium*, which showed the dependence of the 'killer' character on self-replicating particles in the cytoplasm as well as on a gene, and to the possible interest of this

Some Books Received

123

fact, Dr Beale's book – published in the same series of Cambridge monographs – gives the evidence and discusses it.

TEACH YOURSELF BIOCHEMISTRY by P. H. Jellinck (London, English Universities Press Ltd, 1954), pp. 199, 6s.

For those with some knowledge of chemistry this can be recommended as a short and simply written introduction to biochemistry. There are general chapters on cells, methods, and enzymes, and an account of blood and biological oxidation in which enzymes are presented in a functional context. For the rest, the emphasis is on metabolic pathways, vitamins, and hormones, and a surprisingly wide range of information is given. The inclusion of a further introductory chapter which attempts to cover chemistry from the beginning seems over-optimistic.

CHROMATOGRAPHY (*British Medical Bulletin*, Vol. 10, No. 3: London, British Council, 1954), pp. 252, 15s.

A symposium on chromatography planned by a committee under the chairmanship of Dr A. J. P. Martin, who shared a Nobel Prize for its development, makes a worthy addition to the *British Medical Bulletin* series. He comments in his introduction on the fact that it has proved possible to apply chromatographic methods of separation and analysis 'to almost all classes of substances with which biochemistry is concerned'; those here represented include amino-acids, proteins, organic acids, carbohydrates and phosphoric esters, nucleotides and related substances, thyroid hormones, antibiotics and vitamins, and inorganic materials. There are contributions also on principles and practical aspects, including the relatively new method of gas-liquid chromatography (*Science News* 33, p. 114).

RADIOISOTOPE CONFERENCE 1954: VOL. I, MEDICAL AND INDUSTRIAL APPLICATIONS, VOL. II, PHYSICAL SCIENCES AND INDUSTRIAL APPLICATIONS (London, Butterworths Scientific Publications, 1954), pp. 418 and 223, 65s and 45s respectively; set of two vols., 100s.

The value of the first conference, sponsored by the Atomic Energy Research Establishment, Harwell, on the uses of radioisotopes in research, medicine, and industry was shown by the holding of a second conference in July, 1954; the usefulness of its proceedings for

reference is increased greatly by their quick publication, on which both organizers and publishers are to be congratulated.

BIOLOGY OF DESERTS 1954 edited by J.L. Cloudsley-Thompson (London, Institute of Biology, 1954), p. 224, 14s.

A conference on the biology and productivity of hot and cold deserts was held by the Institute of Biology in the autumn of 1952, and, with support from Unesco, was attended by speakers from France, Israel, East Africa, the United States, and Australia. The published proceedings make a useful compendium, from which the work of Dr B. Schmidt-Nielsen on the attainment of water-balance in small desert-living rodents may perhaps excusably be picked out as of special interest.

PHYSICS OF THE PLANET MARS by Gérard de Vaucouleurs (Faber & Faber, 1954), pp. 365, 50s.

Dr de Vaucouleurs has already written an excellent summary of knowledge of *The Planet Mars*. His new book, with acknowledgement to Mrs G. Simonow for help in ensuring correctness of translation from the original French, differs from the old in giving a fuller indication both of the evidence available from observation and of the theoretical arguments used in interpreting it. An outline for a research programme is included.

MAN AND THE PLANETS by R. Richardson (London, Frederick Muller Ltd, 1954), pp. 188, 15s.

This is an essentially 'popular' book on the planets, with roughly half its length given to Mars. The author combines knowledge and enthusiasm, but the latter wins sometimes over logic: cf. the argument – only slightly abbreviated – that animal life is so adaptable that it would be foolish to deny its possibility on Mars, therefore there must be plant life too.

POWER TODAY AND TOMORROW by F. Sherwood Taylor (London, Frederick Muller Ltd, 1954), pp. 192, 15s.

Dr Sherwood Taylor, the Director of the Science Museum, here provides a straightforward and good account of the sources of energy which are available to man, the uses made of them, and foreseeable prospects.

ABOUT OUR CONTRIBUTORS

G. FELDMAN did his undergraduate and some graduate work at the University of Toronto. He then came to Birmingham, where he has been working in field theory and meson physics. He is now a theoretical assistant connected with the Birmingham synchrotron.

D. J. FERRETT, aged 25, was educated at Chichester High School and Merton College, Oxford. He graduated with first-class honours in 1951, and obtained his D.Phil. for research into polarographic techniques, in particular the use of the rotating platinum electrode. He is now continuing research into electro-analytical techniques at the Atomic Energy Research Establishment, Harwell. He is interested in all levels of scientific reporting, is a W.E.A. lecturer, and is gathering together material for a text-book on 'Chemical Electrochemistry'.

R. J. C. HARRIS graduated in chemistry at Imperial College, London, and took a Ph.D. at the Royal Cancer Hospital; is now a Research Fellow of the British Empire Cancer Campaign and investigates avian tumour viruses at the Pollards Wood Research Station of the Royal Cancer Hospital. He has lately completed a term of five years as the first Honorary Treasurer of the Institute of Biology. He edited the report of the Institute's 1951 symposium on *Freezing and Drying*, and also *Biological Applications of Freezing and Drying* for the Academic Press in 1954.

R. J. HARRISON, Professor of Anatomy at the London Hospital Medical College, was educated at Oundle School, Gonville and Caius College, Cambridge, and at St Bartholomew's Hospital Medical College. He has been Lecturer in Anatomy in Glasgow University and Reader in Anatomy at Charing Cross Hospital Medical School; he was awarded (jointly) in 1950 the Symington Prize for research in Anatomy. His interest in reproduction and embryology led to an investigation of reproductive phenomena in whales and seals and thus to more general problems of modifications in diving mammals.

W. MAYS is a Lecturer in Philosophy in the University of Manchester. He studied at the Universities of Oxford and Cambridge, taught at the University of Edinburgh, and assisted Professor Jean Piaget at Geneva and in Norway; is interested in logical machines and applications of logic to psychology and cybernetics.

R. M. TENNENT is an I.C.I. Fellow in the Physics Department of Leeds University. He graduated at London University and, after some years of industrial experience, returned to an academic life and did research at Imperial College, London. He is now studying the interactions of cosmic-ray particles with several different elements. Joint author (with Dr A. J. Herz) of an article in *Science News* 27.

SUBJECT INDEX

Numbers 32-35

References are in all cases to page and number, e.g., 109(35). Articles are indexed under what is judged to be a key-word in their titles (printed in small capitals). Cross-references are suggested under a number of general subject names. Paragraphs under the heading *Research Report* are indicated by (R.R.). Continuing references are, in general, not given.

- Accelerator. *See*: LINEAR
 Adenosine triphosphate in muscular contraction, 110(35)
 Adrian, E. D., 111(32)
 Africa, cattle in. *See*: MILK
 Age of minerals, determination of, 51(34)
 Agriculture. *See*: MILK, WHEAT
 Aleksandrov, 65(32)
 ALGAE, Colony Formation in. (R.R.) 109(35). Phases of development in *Pediastrum duplex*
 Algae for food, 80(32)
 Aller, L. H., 30(34)
 Alloys, analysis of, 63(35)
 Alloys for atomic engineering, 94(32)
 Alluvium, flood-plain, 77(33)
 Ambartsumian, V. A., 26(34)
 Amoroso, E. C., 89(35)
 Anaerobes, continuous cultivation of, 119(34)
 Analysis, by polarography, 55(35)
 Anderson, T. F., 94(33)
 Antigen, as individuality factor, 83(34)
 Aston, F. W., 45(34), Inset: 13(34)
 Astronomy. *See*: CREATION, FREQUENCY, INTERSTELLAR, SKY, SOLAR, STARS
 Astronomical time compared with radio standards, 115(35)
 Atlas, sky, publication of, 119(33)
 Atmosphere, upper, analysis by mass spectrometer, 62(34)
 Atomic bombs, radioactivity from, 107(33)
 ATOMIC Factories, Britain's. 90(32). Scheme for plutonium production, 90; cooling of reactors, 91; purity levels required, 92; fabrication problems, 94; remote control, 95; stages of separation, 96; radioactive wastes, 97; research organization, 98
 Atomic Physics. *See*: BEVATRON, LINEAR, MASS-SPECTROMETER, NUCLEAR, PARTICLES, THEORETICAL
 Aviation. *See*: TAKING-OFF
 Axiomatic method in topology, 61(33)
 Bacteriology. *See*: BACTERIOPHAGE, FREEZE
 BACTERIOPHAGE, Recent Work on. J. E. Hotchin, 89(33). Resemblance to viruses, 89; growth of plagues, 90; 'lysis', 91; process of infection, 92; 'ghost' bacteriophage, 94; phage-resistant bacteria, 97; transfer of virulence, 99. Inset: 23-5
 Baerends, G. P., 16(33)
 Bakelite, 45, 52(32)
 Barendsen, G. W., 117(35)
 Barker, G. C., 70(35)
 Baum, V. A., 118(35)
 Beach, F. A., 20(33)
 Bells, water, 101(32)
 Bernstein, L., 85(35)
 Bethe cycle, 18(34), 21(34)
 Bethe, H. A., 18(34)
 BEVATRON in Operation (R.R.), 118(32)
 Biochemistry. *See*: FREEZE, INDIVIDUALITY, MUSCULAR
 Blaauw, A., 26(34), 32(34)
 BOILING of Liquids, The. J. W. Westwater, 37(34). Irregularities of heat transfer, 38; practical applications, 38; three types of boiling, 39; nuclear, 40; transition, 42; film, 42. Inset: 20-2
 Bok, B. J., 34(34)

- Boltzmann's constant applied to polymers, 58(32)
- Bondi, H., 19(32), 25(32)
- Bone, uranium dating of, 110(33)
- Books Received, 124(32); 125(33); 123(34); 122(35)
- Born, M., 7(32) footnote, 11(32)
- Botany. *See*: ALGAE, CHLORELLA
- Bowie, S. H. U., 110(33)
- Braithwaite, R. B., 7(32)
- Brdicka, R., 67(35)
- Breyer, B., 69(35)
- BRITISH Association (R.R.), 115(34), Summary of 1954 meeting. Cell division, 115; terrestrial magnetism, 117; continuous cultivation of anaerobes, 118
- Brown, J. D., 103(34)
- Burne, R. H., 78(35), 80(35)
- CAMERA, Fastest. (R.R.), 122(34). High speed camera developed at Los Alamos Capenhurst atomic factory, 91(32)
- Carbon-14 dating of sea-beds, 117(35)
- Carnot and Clapeyron (Correspondence), 119(32)
- Carotenoids in insect coloration, 92(34)
- Carothers, W. H., 46(32)
- Cartwright, W. F., 49(35)
- Cascade stage of nuclear disintegration, 40(33)
- Cattle in Africa, 103(34)
- Cell division, availability of energy for, 115(34)
- Cellular parasitization, 95(33)
- Celtic patterns. *See*: TOPOLOGY
- Cepheid variables, 20(32)
- Cerebral cortex, 11(33)
- Cetacea, adaptation for diving, 74(35)
- CHEMICAL Elements, A Century of. (R.R.) 108(32). Newly created elements, 99, 100
- Chemistry, Inorganic. *See*: CHEMICAL, MOLECULES, POLAROGRAPHY
- Chemistry, Organic. *See*: FINGERPRINTS, MOLECULES, POLAROGRAPHY
- CHLORELLA, The Mass Culture of. A. M. Mayer, 80(32). Algae as a food source, 80; high light utilization, 82; protein and vitamin content, 84; industrial methods, 85; separation, 87. Inset: 20
- Chromosomes, as basis of individuality, 71(34)
- chemistry of, 75(34)
- Chromatography, filter-paper, 116(34)
- Clapeyron and Carnot (Correspondence), 119(32)
- Clark, H. M., 108(33)
- Cleland, J., 87(35)
- Climate. *See*: WEATHER
- Cloud chamber in study of nuclear disintegration, 34(33), 28(35); double chamber system, 36(35)
- Colonial Veterinary and Agricultural Services, British, 103(34)
- Coloration of insects. *See*: INSECT CONCEPTS, How We Form. W. Mays. 11(35). Studies by J. Piaget; conservation of concepts, 12; quantity, 13; 'reversibility', 14; number, 16; substance, 16; time and movement, 17; speed, 19; perspective and metric space, 21.
- Contamination, radioactive, 109(33)
- Convertpilanes, 102(33)
- Cortical patterns in sensory response, 113(32)
- Cosmic radiation, 39(33)
- Cosmical Aerodynamics, Symposium on, 31(34)
- Cosmology, relativistic theories of, 22(32) *See also*: CREATION, INTERSTELLAR, STARS
- Cosmotron, 39(33)
- Couch grass, hybridization with wheat, 75(32)
- CREATION, Continuous. Sir Harold Spencer Jones, 19(32). Recession of galaxies, 21; relativistic cosmologies, 22; 'the perfect cosmological principle', 25; mean density and expansion, 26; the observable horizon, 27; the scheme of galaxies, 29; infinity of the universe, 30; form of created matter, 31. Inset: 1, 2
- Creer, K. M., 117(34)
- Crystallinity of polymers, 69(32)
- Cyclotron creation of elements, 108(32)
- Cytoplasm, genetic significance of, 79(34)

- Darwin, Charles, 14(33), 85(34)
- Daubney, R., 102(35)
- Davidson, C. F., 110(33)
- Davies, R. E., 111(35)
- Davis, W. M., 79(33)
- Dawbin, W. H. I., 115(32)
- Dean, J. A., 64(35)
- Density of the universe, 26(32)
- Denaturation of proteins, 93(35)
- D'Herelle, 89(33)
- Diffusion properties of gases, 54(34)
- Dirac's equation, 43(35)
- DIVING Mammals, Adaptations in. R. J. Harrison, 74(35). Early observations, 75; types of vascular plexus, 77; kidney, 78; liver, 80; effect of hydrostatic pressure, 83; lungs, 84; behaviour in diving, 85; amount of blood, 87; hearing, 88; reproduction, 89. Inset: 1-10
- DNA (nucleic acid), 75(34); as genetic determinant, 77(34)
- 'Drive' in animal behaviour, 21(33)
- Dust, stellar. *See*: INTERSTELLAR
- Eccles, J. C., 10(33)
- Ecology, molecular, of cell, 84(34)
- Ecological approach to cattle-raising in Africa, 108(34)
- Eddington, Sir A., 16(34)
- Edwards, W. N., 111(33)
- Egner, W. E., 117(33)
- Einstein, A., 22(32)
- Elastomers. *See*: MOLECULES
- Electrolyte, indifferent, in polarography, 57(35)
- Elements, new chemical, 108(32)
- Energy, source of stars, 13(34); transport in stars, 15(34)
- Engineering, atomic. *See*: ATOMIC ENTOMOLOGY. *See*: INSECT
- Entropy of a strained network, 59(32)
- Essen, L., 116(35)
- Ethology, 15(33). *See*: INSTINCT
- Evaporation stage of nuclear disintegration, 40(33)
- Faegri, K., 66(33)
- Faulkner, D. E., 103(34)
- Fawcett, D. W., 78(35)
- Ferri, C., 56(32)
- Film boiling, 39(34)
- FINGERPRINTS, Chromatography and. (R.R.), 117(32). A new method of print detection
- Fire Offices' Committee, 63(33)
- Fire Research, 63(33). Work of the Joint Fire Research Organization. Use of models. Inset: 1-13
- Flames, spread of. *See*: FIRE
- Fleckenstein, A., 111(35)
- Flohn, H., 75(33)
- Floodorf, E. W., 94(35)
- Fossils, radioactive dating of, 110(33)
- Fowler, W. A., 20(34)
- Franklin, K. J., 77(35)
- Fraser, F. C., 88(35)
- FREEZE-Drying. R. J. C. Harris, 91(35). Preservation of proteins, 91; removal of water vapour at low temperature, 92; development of technique, 93; preservation of serum and plasma, 97; antibiotics, 100; food, 101; microorganisms, 102; tissue-banks, 104. Inset: 14-16
- FREQUENCY and Time, Comparisons. (R.R.), 114(35). Radio accuracy in transmission of time standards. Variations in earth rotation, 115; new transmissions from Rugby, 116. Broadcast frequency transmissions, 115(35)
- Freud, S., 28(33)
- Fry, D. W., 35, 39(32)
- Fry, R. M., 103(35)
- Galaxies, 20(32), Inset: 1, 2(32)
- Games, Theory of, 113(34)
- Gane, R., 101(35)
- Gawn, R. W. L., 76(35)
- Geer, G. de, 75(33)
- Geography. *See*: SEA-BED, WEATHER
- Geology. *See*: SEA-BED
- GEOPHYSICAL Year, International. (R.R.), 112(35). Preparations for observations between July 1957 and December 1958. 'World days' and 'world intervals', 113
- Genes and chromosomes, 72(34)

- Germanium, preparation for transistors, 57(34)
- Glacial maximum, climate of Britain at last, 65(33)
- Gloster-Meteor, 103(33)
- Gold, T., 19(32), 25(32)
- Greaves, R. I. N., 94(35), 103(35)
- Greenstein, J. L., 22(34)
- Haldane, J. B. S., 15, 18(33)
- Hansen, William, 38(32)
- Hardy, G. H., 53(33)
- Harwell, 37(32), 64(32), 90(32)
- Hebb, D. O., 9(33)
- Hediger, H., 27(33)
- Heinroth, O., 24(33)
- Helicopters, 101(33)
- Helium, building up of, from hydrogen, 13(34)
- , use in leak detection, 50(34)
- Herrriott, R. M., 94(33)
- Hershey, A. D., 94(33)
- Hertzprung-Russell diagram, 11(34)
- Heyrovsky, 55(35), 62(35)
- Hill, A. V., 110(35)
- Hinton, Sir Christopher, 90(32)
- Homogeneity of the universe, 25(32)
- Hopwood, F. L., 101(32)
- Hoyle, F., 19(32), 25(32), 16(34), 21(34)
- Hubble, E., 21, 29(32)
- Hufnagel, Charles, 105(35)
- Hulst, H. C. van de, 28(34), 35(34)
- Hunter, John, 75(35)
- Huxley, Julian, 19(33)
- Hydraulics. *See*: WATER BELLS
- Hydrocarbons, analysis by mass spectrometer, 59(34), 64(34)
- Hydrogen, helium-building from, 13(34)
- Hydrogen peroxide in atomic engineering, 94(32)
- Hyperon, 24(35)
- 77; cytoplasmic influence, 79; antigens, 83; ecology of cells, 84
- 'Innate Behaviour', 18(33)
- Inoculation, native method in Africa, 105(34)
- Insectorubins in insect coloration, 89(34)
- INSECT Pigments and Coloration. **B.** Nickerson, 85(34); Pigment and surface factors, 86; exogenous and endogenous pigments, 87; quantities and positioning, 93
- INSTINCT and Learning. S. A. Barnett, 7(33). Reflex responses, 8; cortical structure, 12; study of complex behaviour, 14; releasers or sign stimuli, 16; ethological concepts, 20; adaptation of behaviour, 23; genetic and environmental factors, 25; human applications, 26
- INTERSTELLAR Material. F. D. Kahn, 25(34). Limitations on galactic observation, 24; comparison with outer nebulae, 26; reddening of light, 27; interstellar gas, 29; theory of formation of stars, 31; interstellar polarization, 34. Inset: 1-3
- Irving, Lawrence, 85(35), 88(35)
- Isotopic ratios, determination by mass spectrometer, 51(34)
- , in stars, 23(34)
- Iversen, J., 66(33)
- Janke, J., 111(35)
- Jasper, H. H., 114(32)
- Jay, K. E. B., 90(32)
- Jeffreys, H., 7(32), footnote, 10(32)
- Jenkins, I. L., 70(35)
- Jennings, J. N., 85(33)
- Jessen, J., 74(33)
- Jet-plane braking, 104(33)
- Jodrell Bank Experimental Station, 121(34)
- Kappa particles, 80(34)
- Kells, Book of, 51(33)
- Kemmer, N., 49(35)
- Kennedy, J. S., 22(33)
- Kinked molecules, 59(32)

- computers and operational research, 112
- teachers, qualifications of, 117(33)
- Matthews, L. Harrison, 83(35), 89(35)
- Matthews, P. T., 52(35)
- Meanders, valley, 77(33)
- Medical use of linear accelerators, 39(32)
- Meinke, W. W., 108(33)
- Melanins in insect coloration, 87(34), 93(34)
- Melville, Herman, 75(35)
- Mercury electrode, in polarography, 55(35)
- Mesons, in nuclear disintegrations, 30(33); production in nucleon encounters, 41(33); as addition to fundamental particles, 24(35); symbol for (Correspondence), 123(32)
- Theory of nuclear forces. *See*: NUCLEAR
- 'Metabolic pool', mass spectrometer research on, 56(34)
- Metallurgy. *See*: POLAROGRAPHY
- Meyer, K. H., 56, 59(32)
- Michurin, 73(32)
- Micro-organisms, preservation of, 102(35)
- MILK out of Africa. C. H. Waddington, 103(34). Colonial services, 102; native cattle, 105; problems of social habit, 106; genetic problems, 107. Inset: 9-12
- Millikan, R. A., 27(35), 34(35)
- Mill, John Stuart, 11(32)
- Mills, B. Y., 121(34)
- Milthers, P., 74(33)
- MIND and Matter: A Monist View. J. A. V. Butler, 95(34). 'Perception' and scientific outlook, 95; brain structure, 97; matter and sensation, 100
- Mitchell, H. T., 116(35)
- Mitotic division of cells, significance of 78(34)
- 'critical', 82(34)
- MOLECULES, Large. Michaela Leitner, 43(32). Problems of common natural substances, 43; synthesis of high polymers, 45; industrial research, 46; polymeric materials, fibres, 51; resins, plastics, 52; structure, 53; elasticity, 55; energy relationships, 57; randomly
- Klystron valve, 38(32)
- Kolthoff, I. M., 66(35), 72(35)
- Krebs, H. A., 111(35)
- Laitinen, H. A., 72(35)
- Lauritsens, 20(34)
- Lazurkin, 65(32)
- Learning. *See*: INSTINCT
- Leprince-Ringuet, Prof., 36(35)
- Lemaitre, 23(32)
- Leveque, M. P., 68(35)
- Libby, W. F., 117(35)
- LINEAR Accelerators in Use. P. Howard-Flanders and A. W. Haslett, 33(32). Comparison with cyclic types, 33; gradation of phase-velocity, 35; diagram of electron linear accelerator, 37; as neutron spectrometer, 37; in hospital work, 39. Inset: 3-7. Correspondence, 124(33)
- Liquids. *See*: BOILING of
- Loess, climate and distribution of, 70(33), 85(33)
- Lovell, A. C. B., 121(34)
- Lwoff, A., 97(33)
- 'Lysis' by bacteriophage, 91(33)
- Lysogenic bacteria, 97(33)
- Lytleton, R. A., 21(34)
- McKellar, A., 23(34)
- Magnetron, 34(32)
- Magoun, H. W., 114(32)
- Mass-luminosity relation in stars, 12(34), 22(34)
- MASS SPECTROMETERS, Uses of. M. P. Barnett, 45(34). Use for industrial analysis, 46; design, 47; mass spectrum, 49; leak detection, 50; isotopic ratios, 51; non-radioactive tracers, 55; isotopic dilution, 57; technique of full analysis, 60; use in petroleum engineering, 64. Inset: 13-19
- MATHEMATICS in Industry. N. W. Fox, 109(34). Problems of the arts graduate in industry, 109; statistics, 110; personnel department, 111; electronic

- kinked molecules, 59; glassy state, 66; crystallinity, 67. Inset: 8-17
- Mommaerts, W. F. H. M., 112(35)
- Moner, J. G., 108(35)
- Monod, J., 119(34)
- Morgan, W. W., 32(34)
- MUSCULAR Contraction, Energy of. (R.R.), 110(35). Evidence for adenosine triphosphate as energy source, 110; contra-indications in recent experiments, 111
- Nagana, African cattle disease, 106(34)
- Neumann, von, 113(34)
- Neutrino, 24(35), 30(35)
- Novae, 20(32)
- Nuclear boiling, 39(34)
- NUCLEAR Disintegrations, High-Energy. P. E. Hodgson, 30(33). Impact parameters and internal motions, 31; experimental techniques: Geiger counters, 32; cloud chamber, 34; photographic plate, 35; characteristics of disintegration, 39; nuclear potentials, 42; energy distribution, 45; angular distribution, 46. Inset: 14-20
- NUCLEAR Explosions, Radioactivity from. (R.R.), 107(33). After effects of A- and H-bombs; observations in U.S.A.
- NUCLEAR Forces, Meson Theory of. G. Feldman, 43(35). Interaction inside the nucleus, 43; pion production, 45; properties of pions, 47; pion-nuclear interaction, 51; strength of nuclear forces, 53; recent experiments, 53.
- Nucleic acid in bacteriophage, 93(33)
- in chromosomes, 75(34)
- Nucleons and hyperons, 24(35)
- Nylon, 46, 51(32)
- Nukiyama, S., 37(34)
- Oakley, K. P., 111(33)
- Oceanography. *See*: SEA-BED
- Oechialini, G. P. S., 46(35)
- Odén, S., 117(32)
- Olfactory nerve response, 111(32)
- Oort, J. H., 25(34), 31(34)
- Operational research in industry, 113(34)
- Organic compounds, polarographic analysis of, 66(35)
- Palaeclimatology. *See*: WEATHER
- Panofsky, W. K. H., 50(35)
- PARTICLES, Finding Out about Fundamental Particles. M. Tennent, 24(35). Constants of description, 25; table of established particles, 26; mass, charge and decay, 27; spin, 28; laws of conservation, 29; cloud chamber and emulsion methods of research, 32; lifetime measurements, 38
- Pavlov, I. P., 8(33)
- Pediastrum duplex*, development of colonies in, 108(35)
- Penck, Albrecht, 67(33)
- Penfield, W., 114(32), 97(34)
- Perception, sensory, 111(32)
- Permafrost, 70(33)
- Perry, R. L., 101(32)
- Perspective, children's concepts of, 21(35)
- Petroleum engineering, mass spectrometer in, 64(34)
- Philosophy. *See*: CONCEPTS, MIND, THEORETICAL
- Photographic emulsion methods in particle research, 28(35)
- records of nuclear disintegration, 35(33)
- Photography, high-speed, 122(34)
- Photomeson production, 46(35)
- Photomultiplier, 39(35)
- Photon picture of the electromagnetic field, 43(35)
- Photons and neutrinos, 30(35)
- Physics. *See*: BOILING, FREQUENCY, MASS SPECTROMETER, WATER
- Physiology. *See*: DIVING, MUSCULAR
- Piaget, J., 11(35)
- Pierce, J. A., 116(35)
- Pigments, insect. *See*: INSECT
- Pitdown man, uranium dating of, 111(33)
- Pion, production, 46(35); 'intrinsic parity' of, 49(35)
- Pinnipedia, adaptation for diving in, 75(35)
- Pituitary gland (Correspondence), 123(33)
- Plastics. *See*: MOLECULES

- Pleistocene climate, 65(33)
- Plutonium modifications, 111(32)
- , separation of, 90(32)
- Polarization, interstellar, 34(34)
- POLAROGRAPHY. D. J. Ferrett, 55(35). Properties of mercury drops, 55; reduction potential, 57; conditions for quantitative analysis, 59; polarograms, 59; qualitative analysis, 61; chemical uses, 62; as titration indicator, 64; of organic compounds, 66; recent advances in technique, 68. Inset: 11-13
- Pollen as evidence of ice-age climate, 72(33)
- Polycondensation, 46(32)
- Polymers, high, 43(32)
- Polymerization, 46(32)
- of insect pigments, 89(34)
- Populations, animal and human (Correspondence), 121(32)
- Powell, C. F., 46(35)
- Position effect in chromosomes, 74(34)
- Pribil, R., 64(35)
- Pringsheim, E. G., 109(35)
- Proton-proton chain, 18(34)
- Proton synchrotrons, in experiments on nuclear forces, 53(35). Inset: 16(34)
- Psychology. *See*: CONCEPTS, INSTINCTS, MIND, SENSORY
- Publications, The writing of scientific (Editorial), 7(35)
- Purves, P. E., 88(35)
- Radiative transfer within stars, 15(34)
- Radicals, organic free, 58(34)
- Radio. *See*: FREQUENCY
- Radioactive wastes, disposal of, 97(32)
- RADIO Telescopes. (R.R.), 120(34). New instruments at Cambridge and St Mary's, New South Wales. Inset: 4-8
- Radiotherapeutic Research Unit, 40(32)
- Rainfall, ice-age. *See*: WEATHER
- 'Reaction specific energy', 20(33)
- Reactors, nuclear, 92(32). *See*: ATOMIC
- Reddening of light by interstellar dust, 27(34)
- Reflexes, innate and conditioned, 8(33)
- Relativity, Special Theory of, and cosmic-ray particles mass, 27(35)
- Relativity and cosmology, 22(32)
- 'Releasers' of complex responses, 16(33)
- 'Renormalization' in quantum electrodynamics, 51(35)
- Resins, thermoplastic, 51(32)
- Retia of diving mammals, 77(35)
- Reversibility of concepts, 14(35)
- RNA (nucleic acid), 75(34), 81(34)
- Roth, F., 68(35)
- Roubal, Z., 64(35)
- ROYAL Society Conversazione. (R.R.), 112(33). Report of May 1954 meeting
- Rubber, synthetic, 45, 49, 52, 55(32)
- Ryle, George, 19(33)
- Ryle, M., 120(34)
- Salam, A., 52(35)
- Salpeter, E. E., 20(34)
- Sandage, 21(34)
- Santangelo, J. G., 39(34)
- Scholander, P. F., 88(35)
- Schrodinger's equation, 43(35)
- Schwarzschild, 21(34)
- Science teachers, qualifications of, 116(33)
- SEA-BED History. (R.R.), 117(35). Carbon-14 dating of shells and peat from Gulf of Paris and Dutch coast
- Seals. *See*: DIVING
- SENSORY Perception. (R.R.), 111(32). Reviews by Dr E. D. Adrian. Olfactory 'patterns', 112; cortical projection, 113
- Serum, preservation by freeze-drying. *See*: FREEZE
- Sitter, De, 22(32)
- SKY Atlas. (R.R.), 119(33). Announcement of publication by N. G. S. and Palomar Observatory
- Shackell, L. F., 93(35)
- Sherrington, 9(33)
- Shotton, F. W., 86(33)
- Slipher, V. M., 19(32)
- 'Social properties' of stars, 9(34)
- SOLAR Energy. (R.R.), 118(35). Solar heating apparatus in use
- Solid Particles in Astronomical Objects, Symposium on, 31(34)
- Solifluxion, 67(33)
- Soviet wheat experiments, 73(32)
- Spalding, Douglas, 15(33)

Spectrograph, mass, 745(34)
Spectrometers. See: **MASS SPECTROMETERS**
Spence, R., 95(32)
SPHENODON Reared in Captivity. (*R.R.*), 115(32)
Sphincter, caval, in diving mammals, 81(35)
 'Spin' of a particle, 28(35)
Spitzer, L., Jr., 32(34)
Springfield atomic factory, 91(32)
Spurway, 18(33)
Staudinger, H., 50(32)
Staphylococcus aureus. Inset: 24-5(33)
STARS, The Energy of the. **C. M. Bondi** and **H. Bondi**, 7(34). Theory of stellar structure, 7; primary data, 8; Hertzprung-Russell diagram, 10; mass-luminosity, 12; release of nuclear energy, 13; gravitational and pressure energies, 14; importance of radiative transfer, 15; thermo-nuclear reactions, 17; helium-richness, 21; isotopic ratios, 23.
Statistical model of nuclear disintegration, 39(33)
Steinberger, J., 49(35)
Stellar structure, theory of, 7(34)
Sticklebacks, behaviour of, 17(33)
Strömgen, B., 32(34)
Sublimation, vacuum. See: **FREEZE**
Sun temperatures, 22(34)
Swann, M. M., 115(34)
Szent-Gyorgyi, A., 111(35)

Tacnodes, 55(33)

TAKING OFF and Landing, New Ways of. **J. M. Stephenson**, 101(33). Airfield problems of jet planes, 101; 'convertiplanes', 102; jet brakes, 104

TEACHERS, School Science. (*R.R.*), 116(33). Report of investigation in Lancashire and Cheshire. Comparison with Report by National Advisory Council on Training of Teachers (1953)

Technology. See: **ATOMIC**, **MATHEMATICS**, **MASS SPECTROMETERS**

Terrestrial magnetism, symposium at Oxford, 117(34)

Terylene, 46(32), 51(32), 70(32)

Thackeray, A. D., 21(32), 33(34)

THEORETICAL Entities, The Existence of. **Bernard Mayo**, 7(32). Methods in philosophy of science, 7; science and common sense, 11; particularity of electrons, 13; habits of description, 14; theoretical concepts, 16. Correspondence, 120(33)

Theory of Games, 113(34)

Thermodynamics of elasticity, 57(32)

Thermo-elastic effect in rubber, 56(32)

Thermo-nuclear reactions in stars, 17(34)

Thomson, J. J., 33(35)

Thorpe, W. H., 23(33)

Tinbergen, N., 16(33), 21

Tissue, preservation for transplantation, 104(35)

Tomlinson, J. D. W., 81(35), 85(35)

Topological concepts in children, 20(35)

TOPOLOGY, Celtic Interlacing Patterns and. **H. A. Thurston**, 50(33). Under- and over-patterns of closed curve, 50; theoretical treatment, 55; axiomatic method, 61. Correspondence, 120(35)

Tracer elements, non-radioactive, 55(34)

Transition boiling, 39(34)

Treloar, L. R. G., 60(32)

Tuataras, rearing in captivity, 115(32). Inset: 26

Twort, F. W., 89(33)

Tyndall, J., 100(34)

URANIUM Dating of Bone. (*R.R.*), 110(33). Method used on Piltdown man

V2 rockets, 103(33)

Vacuum sublimation. See: **FREEZE**

Valley meanders, 77(33)

Varves, as climatic records, 75(33)

Vertical flight, 102(33)

Viscosity of high polymers, 50(32)

Vitamin A, insects without, 93(34)

Vries, Hl. de, 117(35)

Walmesley, R., 78(35)

WATER Bells. **G. N. Lance**, 101(32). The phenomenon, 101; variations of shape

103; experimental methods, 104. Inset: 21-5

WEATHER. Climate and River Erosion in the Ice Age. **G. H. Dury**, 65(33). Progress of palaeoclimatology, 65; glacial maxima, 66; soil-flow, 67; permafrost, 70; dating by loess, 70; fossils, 71; plant remains, 72; post-glacial climate, 73; clay and sand laminae, 75; valley windings, 77; quantitative studies, 87

Webb, J. H., 107(33)

Weisskopf, V., 43(33)

Whales. See: **DIVING**

WHEAT, Rejuvenated. **N. V. Tsitsin**, 73(32). Hybridization with couch grass in U.S.S.R., 75; hybrid peculiarities, 76; other hybrids, 79. Inset: 18-19

Whipple, F. L., 32(34)

Willard, H. H., 64(35)

Willett, H. C., 75(33)

Williams, Robley, 107(35)

Windscale atomic factory, 91(32)

Wislocki, G. B., 77(35), 84(35)

Wright, Norman, 105(34)

X-ray film, radioactive fogging, 107(33)

Young, A., 117(33)

Young, Thomas, 86(34)

Yukawa, H., 43(35)

Zeuner, F. E., 71(33)

Zoology. See: **DIVING**, **FREEZE**, **INSTINCT**, **MILK**, **MUSCULAR**, **SENSORY**, **SPHENODON**

Numbers 32–35

Further information about any author is to be found in the column *About our Contributors*, which appears in each issue. The numbers in brackets indicate the number of the volume.

2

Barnett, M. P., 45(34)

Bond, C. M., 7(34)

Bondi, H., 7(34)

Butler, J. A. V.,

1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 26

Feldman G 42(25)

Feldman, G., 42(35)
 Ferrett, D. J., 55(35)

* *For. N. W.* 100(34)

Fox, N. W., 109(34)

Harrison, R. J., 74(35)

Hartlett, A. W., 33(32), 108(32), 107(33)

115(34), 108(35)

Hodgson, P. E. 30(33)

Hatchin. *FE* 80(33)Holchin, J. E., 89(33)
Horned Lizards, 3

Howard-Flanders, P., 33(32)

TABLE 1. *Continued*

Lance, G. N., 101(32)

Leitner, Michaela, 43(32)

Mayer, A. M., 80(32)

Mayo, Bernard, 7(32)

Mays, W., 11(35)

Nickerson, B., 85(34)

Stephenson, J. M., 101(33)

Tennent, R. M., 24(35)

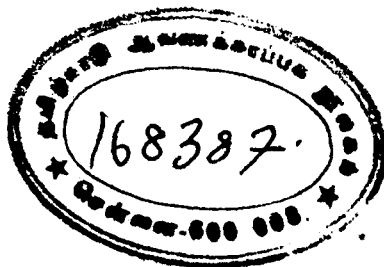
Thurston, H. A., 50(33)

Tsitsin, N. V., 73(32)

Waddington, C. H., 103(34)

Westwater, J. W., 37(34)

Wyburn, G. M., 70(34)



SCIENCE NEWS

Outstanding articles from recent issues include :

SCIENCE NEWS 31

Solvable and Unsolvable Problems: *A. M. Turing*
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Fundamental Particles: The Present Position: *P. E. Hodgson*
Chemical Radiomimetic Agents and Cancer: *R. F. Homer*
Interferometry in Astronomy: *W. H. Marshall*
Weed Control: *R. N. Higinbotham*

SCIENCE NEWS 32

The Existence of Theoretical Entities: *Bernard Mayo*
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A. W. Haslett*
Large Molecules: *Michaela Leitner*
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N. V. Tsitsin
The Mass Culture of Chlorella: *A. M. Mayer*
Britain's Atomic Factories
Water Bells: *G. N. Lance*

SCIENCE NEWS 33

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High-Energy Nuclear Disintegrations: *P. E. Hodgson*
Celtic Interlacing Patterns and Topology: *H. A. Thurston*
Fire Research
Weather, Climate, and River Erosion in the Ice Age: *G. H. Dury*
Recent Work on Bacteriophage: *J. E. Hotchin*
New Ways of Taking Off and Landing: *J. M. Stephenson*

SCIENCE NEWS 34

Mind and Matter: A Monist View: *J. A. V. Butler*
Milk out of Africa: *C. H. Waddington, F.R.S.*
Insect Pigments and Coloration: *B. Nickerson*
The Boiling of Liquids: *J. W. Westwater*
Uses of Mass Spectrometers: *M. P. Barnett*
Interstellar Material: *F. D. Kahn*
Biological Individuality: *G. M. Wyburn*
The Energy of the Stars: *C. M. Bondi and H. Bondi*
Mathematics in Industry: *N. W. Fox*
Research Report