these very theories, after a hundred years of estrangement. All these years Pure Mathematics has dwelt with pride on its security from utilisation, and even Applied Mathematics has had little in common with the things of actual interest to the laboratory-dwellers, who have got on very well with the works of Euler and Lagrange. But in 1925 Quantum Mechanics was born, and its language, it is found, is precisely the new synthesis of algebra, continuous groups, and "spectral theory" that is so prominent in modern mathematical interest. But the unity goes deeper; for, in the hands of Einstein and Dirac, Physics itself, so steadfastly constructive since Newton's time, has become axiomatic, in the very sense of this account: it is built up from a body of abstract axioms, whose choice is governed only by the needs of the subject itself—that is, by the necessity of agreeing with experiment when suitably interpreted—without regard to any violence that may be done to established methods of thought or metaphysical beliefs.

It is an exciting moment in the history of both subjects.

THE CRAFT OF EXPERIMENTAL PHYSICS

By P. M. S. BLACKETT

I

MORE has been written of what the experimental physicist has discovered than of how he has discovered it. Because he has changed the technique of living by his intense curiosity to find out about obscure things, many of his discoveries have become common knowledge. But his method of experimental discovery, how he works and thinks, is much less known. This may be due to the diversity of his work. For the experimental physicist is a Jack-of-All-Trades, a versatile but amateur craftsman. He must blow glass and turn metal, though he could not earn his living as a glass-blower nor ever be classed as a skilled mechanic; he must carpenter, photograph, wire electric circuits and be a master of gadgets of all kinds; he may find invaluable a training as an engineer and can profit always by utilising his gifts as a mathematician. In such activities will he be engaged for three-quarters of his working day. During the rest, he must be a physicist, that is, he must cultivate an intimacy with the behaviour of the physical world. But in none of these activities, taken alone, need he be pre-eminent, certainly not as a craftsman, for he will seldom achieve more than an amateur's skill; and not even in his knowledge of his own special field of physics need he, or indeed perhaps can he, surpass the knowledge of some theoretician. For a theoretical physicist has no long laboratory hours to keep him from study, and he must in general be credited with at least an equal physical intuition and certainly a greater mathematical skill. The experimental physicist must be enough of a theorist to know what experiments are worth doing and enough of a craftsman to be able to do them. He is only pre-eminent in being able to do both.

In earlier days, when the systematic investigation of natural phenomena was beginning, the natural philosopher required little more technical skill than that of a handyman, and no more mathematics than simple algebra and trigonometry. But the phenomena left unexplored by three centuries of investigation are only to be approached by means of a highly specialised technique and are only to be understood in the light of a highly abstract theory. An intimate knowledge of current physical theory is required to know what experiment to do, and a high technical ability is required to carry the experiment out.

A rapid change is taking place in the technique of experimental physics. New methods are constantly being invented, and each new advance of technique increases our knowledge of the physical world by making possible experiments which before were technically impossible. In part these changes come from within the laboratories themselves, from the technical innovations both of those engaged in fundamental research and of others who may have specialised in the study of a single method, with little care for the results to be obtained by its use. But to an important extent the technique of the experimental physicist is influenced by the technical achievements of industry. The relation is reciprocal. A discovery in a laboratory in one decade leads to an industry in the next. And the purely commercial products of the industry may provide ready-made the instruments to extend the field of the technically possible. The wireless valve and the photographic plate provide examples of indispensable aids to modern research, which have been rapidly carried by an industrial demand to a pitch of refinement which would be far beyond the resources of a research laboratory.

Since industry is constantly improving its products, a laboratory must keep itself acquainted with these developments, for a more sensitive photographic plate or a valve with a new characteristic may make possible or easy what was before impossible or difficult. Not all physical research, of course, requires the application of the latest refinements

of technique, but any experiments which can be attacked successfully by the routine application of well-established methods are likely to be relatively unimportant or at any rate somewhat far from the main line of contemporary advance. For the number of able workers scattered over the world is so large and their acquaintance, both through literature and through personal contacts, with each other's work is so intimate, that there can necessarily be but few chances that an important but easy experiment will remain long unperformed.

The technical equipment required by an experimenter varies greatly according to his field of research, and conversely his choice of subject will often be mainly determined by his special aptitudes. If he is gifted as a glass-blower his interest will turn towards experiments in which he can make good use of his skill. If he is trained as an engineer he will be able to attack problems requiring heavy and complicated machinery for their solution. But in whatever field he works he must become a moderately but not necessarily a highly skilled worker. He must design his apparatus, and in most cases he must also build much of it himself. Laboratories differ in the extent to which assistance from professional glass-blowers, mechanics and general laboratory assistants is available, but the organisation and tradition of most English research laboratories requires that the experimenter shall rely mainly on his own resources. It is not perhaps fanciful to relate this tradition to the vogue of practical hobbies, which already in the last quarter of the nineteenth century led to such typical publications as the periodical *Amateur Work*. Here could be found advice as to how to build one's own organ, bind one's own books or construct a hundred and one articles of use or diversion. So perhaps English experimental physics has derived strength from the social tradition and moral principles which led the growing middle class to spend the leisure of its prosperity in the home rather than the café. Certainly the way of a researcher is hard who does not in some degree delight in handywork for its own sake. However much his theoretical interest may be excited by the problem he is to investigate, he may feel a certain dismay on being assigned a room empty perhaps of all but a table, a blow-pipe and a few tools. Often two years may elapse before definite results come in sight; two years occupied with carpentering, metal work, glass-blowing, and the wiring of electric circuits. Even when an apparatus is completed, an endless succession of minor difficulties and mishaps may postpone its successful use. A glass tube may crack overnight, a single hair may short-circuit an electrometer, a filament may burn out, or the failing of the water supply may wreck an elaborate apparatus. But almost the worst trials to the experimenter's patience are due to leaks, and a considerable portion of his time is often spent in finding them. An experimenter was once heard to complain, "I have spent two days in getting the leak in my apparatus so small that it will now take me a week to find it". If the experimenter does not find pleasure in such activities, that is, if he has not in some degree the temperament of the amateur craftsman, much of his work must be a weariness.

Taken singly, the qualities of hand and mind required to make a good experimental physicist are not rare. But the combination of these abilities in one individual with the right temperament to use them to the full is rare. Many a theoretically gifted student may fail, while learning to be an experimenter, through clumsy fingers, and an adept with a blow-pipe may neither know what experiments are most worth doing nor appreciate the significance of what he has done. Great manipulative skill is by no means essential for an experimenter. But the good experimenter must possess the power of designing an apparatus that can work, and of actually making it do so. He must be able to spot faults quickly and must be able to judge between the various possible causes of failure. It is hard to acquire this facility except by actually handling apparatus, and during this process of learning to be an experimenter, actual manipulative skill plays an important part. But once it is acquired, the handling of apparatus may often be delegated. The greater the experimenter's gift of understanding intuitively how an apparatus works, the less does he need actual manual skill.

This traditional amateur method of research leads naturally to a preference for the simplest possible apparatus. In the early days of the investigation of the properties of radioactive bodies many important researches were carried out with little more apparatus than an electroscope consisting of a piece of gold leaf suspended from a sulphur bead attached to the inside of a tin can. An optical apparatus of cardboard, with cheap lenses attached to corks with wax, will often be as effective as an expensively made telescope and an accurate optical bench, and may often be preferable, both for the ease of alteration and for the practical insight its use demands into the essentials of the experiment. But to-day there are few experiments which do not need apparatus of some complexity and many which need such refinements of technique that they tax the resources of a single experimenter. To some extent the difficulty is being met by team work. The collaboration of an electrical engineer, a radioactive chemist, and an expert in valve circuits, may make possible an experiment which would be impossible for one alone.

Once the subject of an investigation is chosen and the method roughly outlined, the experimenter must build his apparatus. This will consist in part in the setting up of standard pieces of apparatus, galvanometers, magnets, valves, spectroscopes and the like. This activity is often of a routine nature. But these standard instruments are usually subsidiary to some one part of the apparatus which claims the full ingenuity and skill of the experimenter. This part, at least, he will have designed himself, and often he will have made it too.

A majority of present-day experiments involve some vacuum technique and this is hard to standardise. Often complicated mechanisms must be enclosed in glass vessels and then evacuated and baked out to a temperature of several hundred degrees centigrade. Sometimes it is possible to seal up such an apparatus completely in an all-glass vessel, but this requires exceptional skill as a glass-blower or recourse to a professional. Once done, the smallest alteration may involve weeks of rebuilding. So usually an apparatus of this type is made in sections, these being fitted together and made tight against a leakage of air into the apparatus by the use of a grease or cement. It is curious that the most universally successful vacuum cement available for many years should have been a material of common use for quite other purposes. At one time it might have been hard to find in an English laboratory an apparatus which did not use red Bank of England sealing-wax as a vacuum cement. If its pre-eminence is now being shaken, it is not by some refined product of laborious research but by ordinary plasticine. It is hardly possible to exaggerate the controlling importance of such simple technical matters, however trivial they may seem to be. For instance, in a recent investigation of the disintegration of elements by fast protons, it was necessary to make some very large discharge tubes. The detailed design of these tubes is a matter of curious subtlety. The exact shape and position of the electrodes is of great importance and can only be found by trial and error. To have the complete tubes made especially by commercial firms would be very expensive and many weeks' delay might result from the necessity of making some trivial alteration to the electrodes. Even to cement these tubes together with sealing-wax would involve building an oven some fifteen feet high to heat the tubes to the softening point of the wax, and many hours would be required for the heating and subsequent cooling. But the introduction of plasticine as a sealing material has so facilitated the whole technique that when, for instance, a rectifier filament burns out, the great tubes can be dismantled, the filament replaced, the tubes re-erected and resealed, and an X-ray vacuum again obtained in an hour or two.

The rapidity with which an alteration to an apparatus can be carried out is a matter of primary and not of secondary importance. If a day's work is required to test out an idea, it may be done; if a week's work, it may not be done at all.

So even when professional assistance is available, many experimenters prefer to make their own apparatus, however amateurishly. It is very often so very much quicker. For if the aid of a mechanic is called in, scale drawings will have to be made, and it is often easier to construct a small piece of complicated apparatus than to make a drawing of it. The designing of a new type of apparatus is a craft to be learnt in the workshop as well as in the drawing office. Not before the experimenter has succeeded in making it can he say just what he wants to make. For he cannot know what he wants to make without knowing the properties of the materials he will use, and often it is only by handling the materials that their properties can be fully appreciated.

It would be interesting if we could estimate the influence that has been exerted on the history of physics by the more or less accidental properties of easily available substances. How much might physics have been retarded if there had been available no such invaluable materials as glass and rubber, or if the metal mercury had not possessed the peculiar property of being a liquid at ordinary temperatures?

It is obvious that the performance of an engineering structure such as an aeroplane depends directly on the strength of the materials available for its construction. But it is also true that our knowledge of nature is limited by the properties of the materials available for the construction of experimental apparatus. In almost every experiment there is some part which sets a limit to the performance of the whole, and which does so by having already utilised to the limit the properties of the available materials. The strength of a quartz fibre or a cellophane window, the breakdown voltage of transformer oil, or the saturation permeability of iron, are typical of the controlling factors which set temporary limits to our knowledge of natural phenomena, and it is in overcoming these limitations, both by ingenuity in design and by the discovery of new materials, that much of an experimenter's time is occupied.

This dependence of our knowledge on the skill of our hands causes the history of a science to be closely related to the history of practical technique. To know more, more skill must be acquired in the use of old instruments and of old materials, and the development of new. For instance, if we wish to see farther into the distant parts of space, new methods of making the mirrors of reflecting telescopes are required. Perhaps almost the largest possible reflector of glass has already been made; if it is found possible to utilise fused quartz for this purpose, it may be possible to make still larger telescopes and so to see farther still.

Many cases could be quoted, especially in the field of optics (where a particularly high degree of skill is required in the manufacture of instruments) in which an experiment has been planned but has had to wait many years for the skill to be acquired to perform it. Between Fizeau's conception of the interference method of measuring the angular diameter of stars and its successful performance by Michelson, more than fifty years elapsed.

After the invention of a new method or a new instrument progress is often rapid. Then when its limit of usefulness has been reached, investigation may halt, to await the invention of some new contrivance which will allow of further advance. An example of this can be seen in the part played by the scintillation method of detecting alpha particles, and by the way that it reached temporarily the end of its usefulness, to await the application to atomic problems of the wireless valve. The scintillation method is of such beauty and simplicity, and experiments made possible by it have had so profound an effect on physics, that it is of interest to describe it in some detail. It was in fact by the use of scintillations that the experiments were made on which the nuclear theory of the atom was founded in 1911 by Rutherford, and the method has been in almost continuous use in the Cavendish Laboratory since 1919 when he became Cavendish Professor of Experimental Physics and initiated the intensive experimental study of the structure of atomic nuclei.

Of the wonderful results that have been obtained from

these investigations there is little need to write; they are now part of the great system of our knowledge of the physical world, and of this much has lately been brilliantly written. But a description will be given of some of the technical methods that have made these discoveries possible.

II

A minute fraction of the substances out of which the earth's crust is composed are radioactive, that is they break up spontaneously to form new elements. Not only is the investigation of these rare processes of extreme interest, but radioactive bodies have provided the experimenter with an unrivalled method of investigating the atomic structure of other elements. They have done this by providing sources of atomic particles of such great energy that they can be used as tools to explore the structure of other nuclei. In particular, the alpha particles, or nuclei of helium atoms, which are emitted from many radioactive substances, have such a great velocity that they can penetrate the field of force surrounding the nucleus of an atom and so can be used to investigate its structure. Till recently, the possibility of these investigations has depended entirely on the curious and almost accidental fact that these alpha particles can be detected individually by the scintillation method.

If certain crystals are observed under a microscope while being bombarded by alpha rays from some radioactive preparation, a number of tiny flashes of light can be seen. Each of these scintillations is due to the impact of a single particle. By some complicated process, a large part of the energy given up by a particle when it strikes the crystal is converted into a tiny flash of light sufficiently intense to be seen easily by aid of a low power microscope.

The only crystals with which bright scintillations can be obtained are those of zinc sulphide, though much weaker ones are found with certain other substances, including some kinds of diamond. But it is by no means all zinc sulphide crystals which show these scintillations. Pure crystals give none; apparently certain impurities must be present in minute proportions—a one ten-thousandth part of copper salts seems most effective. This beautiful method, dependent on the curious property of one, just sufficiently impure, substance, remained for many years an unrivalled instrument for the investigation of atomic phenomena.

Such experiments were those in which the structure of atomic nuclei was investigated by finding what happened when fast alpha particles made collisions with them. The experimental basis on which the nuclear theory of the atom had been founded by Rutherford was the discovery that the scattering of fast alpha particles by *heavy* elements was such as to indicate that the electrical forces of interaction between the two particles varied inversely as the square of their distance apart, just as do the gravitational forces between a comet and the sun.

The later investigations of Rutherford and his school of workers during the years 1919 to 1924 were concerned mainly with the investigation of the scattering of alpha particles by *light* elements, for with these one might expect to find deviations from the inverse square law, for a light nucleus exerts a much smaller force on an alpha particle than a heavy one does, so that an alpha particle may be expected to approach sufficiently close to make a direct collision. This was found to be the case. In particular, the collisions of fast alpha particles with hydrogen and helium nuclei were found to be many times more frequent than was to be expected on the assumption that the forces obeyed the simple law of the inverse square. It became possible therefore to deduce from the amount of the anomalous scattering the approximate size of the nuclei themselves.

More striking results still were obtained when other light elements such as aluminium were bombarded by alpha particles. It was found that scintillations were observed on a zinc sulphide screen even when quite thick absorbers were placed between the aluminium and the screen. Particles were therefore emitted from the aluminium with much

greater penetrating power than the original alpha particles bombarding the aluminium. This result was interpreted as indicating that some of the alpha particles had caused the disintegration of aluminium nuclei by ejecting from them hydrogen nuclei with great energy. These experiments were the first to show the artificial transmutation of one element into another, and at the time when they were first carried out, their possibility depended entirely on the scintillation method.

The apparatus required for such experiments is surprisingly simple. A radioactive preparation giving off alpha particles is deposited on a metal disc. Close to it is placed a thin sheet of aluminium, then some mica absorbing screens and finally a zinc sulphide screen and a microscope to observe the scintillations. The experiments consisted in counting the number of scintillations on the zinc sulphide screen when different thicknesses of mica were placed in the path of the particles.

The observers, having already spent half an hour or so in the dark to let their eyes reach their maximum sensitivity, so as to be able to see the scintillations clearly, sit in turn at the microscope and watch the faintly illuminated field of view with its slightly granulated appearance, due to the crystals of the zinc sulphide. A bell is rung automatically at intervals of one minute and during each period the observer concentrates his attention on keeping the screen in focus so that every tiny flash may be counted; none must be missed and none imagined. It is not easy to avoid either fault if the scintillations are weak and if the screen is flickering with light produced by the accompanying beta and gamma rays. Especially is this so if the observer has some preconception of how many particles are to be expected. So it is wise to keep him in ignorance of any changes made in the apparatus between observations, so that he shall not know what number of particles to expect.

The difficulty in these experiments was to obtain strong enough radioactive sources to give a reasonable number of scintillations every minute on the zinc sulphide screen. The size of the radioactive sources available is set both by the expense of the parent radioactive bodies and the difficulty and danger attending the use of very large sources. The counting cannot be continued for long periods to make up for the small number of the particles under observation, both because the radioactive sources that have generally to be used are not constant in strength but decay to half their intensity in less than half an hour, and because of the severe strain on the eyes of those counting the scintillations. So work by this method was very slow.

Though the scintillation method proved of the utmost value for the pioneer investigations of anomalous scattering and artificial disintegration, it became laborious when the main outlines of the phenomena had been investigated and when consequently the interest lay in the finer details. For to study these finer details narrower beams of particles are required, and this inevitably still further reduces the number of particles observed.

All such measurements of the intensity of scattering by counting the particles scattered in a given time suffer from an uncertainty due to probability fluctuations. Under identical conditions the number of particles observed in successive periods of, say, one minute, will not be the same but will vary from minute to minute. The more particles that are counted, the more accurately will the observer know the number he wants to know—the average number to be expected in a given time. But it can be shown from the mathematical theory of probability, that if he counts N particles, then his result will be uncertain by an amount $\sqrt{N}$. So if he counts 100 particles his error is 10 per cent.; if 10,000, it is 1 per cent. To increase the accuracy by a factor of ten it is necessary to increase the number of particles a hundred times. From this law, as from other statistical laws, there is no appeal. For accurate work very large numbers of particles must therefore be counted, and to do this by the scintillation method is prohibitively laborious. New methods are therefore required.

As early as 1908, Rutherford and Geiger had detected single alpha particles electrically by magnifying the ionisation due to them by using the process of ionisation by collision. The charged molecules, or ions, produced in a gas by the passage of an alpha particle were accelerated by an electric field to such an extent that they were able by collision with other molecules to break them up to form new ions. These again were accelerated by the same electric field and so produced still more ions, and so on, till the electric current due to all the ions, produced indirectly in this way by one alpha particle, became great enough to be directly detected. But this method failed to find general application owing to the disturbing effect of the strong beta and gamma rays which unavoidably accompany the alpha rays from most radioactive sources. What was wanted was an electrical method which would record single alpha particles even in the presence of a strong disturbing background due to beta and gamma rays.

The advent of the wireless valve made this possible, by putting into the hands of the experimenter a beautiful instrument of the utmost flexibility and power. Just as by artificial distortion the wireless engineer can turn bass voice to tenor, so the physicist, by adapting similar methods, can magnify enormously the sudden burst of current due to an alpha particle without magnifying to the same extent the fluctuating background of ionisation due to the disturbing rays. Once this technical problem had been solved rapid progress in the investigation of the nucleus again became possible. The apparatus required to detect single particles electrically by amplifying with valves the minute ionisation currents produced by them is very much more complicated than the older method of scintillation. It may consist of a five-valve amplifier carefully designed so as to give a very high amplification and yet to be stable and reliable. The transitory current produced by the ionisation due to the alpha particle is magnified enough to give a loud click in a loud speaker or more usually to give a sudden deflection to a high frequency galvanometer. By recording the amplified currents on moving photographic paper, a continuous record of the particles under observation can be obtained, extending over hours at a time. In this way, not only can the accuracy of the observation be taken far beyond that possible with the scintillation method, but phenomena can be observed, in which the rarity of the events puts the experiment quite outside the scope of the earlier method.

Yet another product of industrial research, the thyratron, was to prove an invaluable addition to the physical laboratory. This new type of three electrode valve contains mercury vapour instead of being completely evacuated of all gas, as are ordinary valves. Consequently such a valve has a special kind of characteristic curve which enables it to be used as a very quick relay. By this means, it is easy to cause the surge of current from the amplifier due to a single alpha particle to click over a mechanical counter such as is used in a telephone exchange to register the number of calls from a subscriber. The number of alpha particles arriving in a given time is then read directly from the telephone counter. By elaborating such devices, it has been found possible to count particles even when arriving as often as 2000 in a minute. The effective speed range of counting particles by scintillation lay between, perhaps, one and one hundred particles a minute. The valve and thyratron have widened the range many times.

The only rival to the supremacy of the valve amplifier as a means of counting single particles is the beautiful electrometer of Hoffmann. This instrument is only suitable when the particles are arriving very infrequently, but very important results have been obtained by its use. The delicacy of its construction is however likely to prevent its becoming as widely adopted as the valve amplifier.

In addition to the new technical possibilities furnished by these new instruments, a step of great importance was the production of very large radioactive sources of polonium. Polonium, the last active member of the uranium series of

radioactive elements, is unique amongst radioactive sources in that it gives only a single group of homogeneous alpha particles, accompanied by no appreciable beta or gamma radiation. In addition it has a comparatively long life, decaying only to half its strength in 140 days. Its freedom from other disturbing rays and the comparative constancy of its activity make it the ideal source for many purposes. Since polonium is a radioactive descendant of radium, it is to be found in all old solutions of radium salts or on the walls of any vessel in which radium emanation has been allowed to decay. Most laboratories which specialise in radioactive work possess half a gramme or so of radium, usually kept in solution in a glass vessel. In any such vessel that has been left undisturbed some years, a large store of polonium will have collected. But the danger involved in the manipulation of such large quantities of radium causes the vessel to be left undisturbed as much as possible and so the polonium cannot be extracted. Consequently the supply of polonium must be obtained from the walls of glass tubes that have contained radium emanation. The extraction of the polonium is quite easy; the difficulty is to obtain the tubes. Now polonium has, at present, no commercial value. It is seldom bought or sold, being literally without price, though invaluable to the experimenter. When obtainable at all, these tubes are usually acquired as a gift from some hospital, for the hospitals own the great majority of the world's supply of radium and have no use for the polonium. Unfortunately it is only in a few cases that radium emanation is utilised for therapeutic purposes in ways which facilitate the delivery of the final active product polonium over to the physicist.

It is only in the last few years that such strong preparations of polonium have been utilised successfully for experiments on artificial disintegration, but the results obtained by their use have already been of the highest importance. By this means Bothe and Becker in Berlin were enabled to detect the existence of a highly penetrating radiation emitted when certain light elements, in particular beryllium, are bombarded by alpha particles. These rays had eluded discovery until large polonium sources were available, since all other radioactive sources themselves give a gamma radiation many times more intense than that due to the bombardment of a substance with alpha rays. The further study of these rays by Curie and Joliot in Paris revealed queer features which threw doubt on the original assumption that they were penetrating electromagnetic rays. Still further study by Chadwick led him to attribute some of the properties of the rays to the presence of a new type of particle, the neutron. Thus the discovery of the neutron, a discovery of the utmost importance, has depended technically on the preparation of large sources of polonium and on the development of the valve amplifier and Hoffmann electrometer to detect the ionisation due to single particles. The important part played by the cloud method in this discovery will be described later.

By the use of these new methods, it has proved possible to investigate the process of the artificial disintegration of light elements in a detail far beyond the powers of the older methods. Bothe and Fränz further discovered that when the element boron is disintegrated by bombardment with alpha particles, the protons emitted fall into several groups with different energies. Further study in the Cavendish Laboratory has shown that the same type of process, but often very much more complicated, occurs with other light elements. In this way, it became possible to investigate the energy levels of light nuclei, and so to obtain the first quantitative evidence as to their actual structure.

The structure of heavy nuclei is not so easily open to investigation by bombardment with alpha particles since there are no such particles known which have sufficient energy to penetrate the large electric fields which surround them. But the structure of the heavy *radioactive* nuclei can be investigated by studying the energies of the rays emitted during their spontaneous disintegration. These energies have been known with fair accuracy for many years, and the new

experiments were directed therefore towards attaining an increased accuracy and resolving power. A technical step of importance for this work was the construction by Cotton in Paris of a great magnet, which gave a strong magnetic field over a larger space than had ever been obtained before. By deflecting the alpha particles with this magnet and detecting them by their effect on a photographic plate, Rosenblum showed that the alpha particles from certain radioactive bodies, which had previously been thought to be all of one velocity, actually consisted of several distinct groups with slightly different velocities. Investigation of this fine structure of the alpha particle groups proceeded very rapidly in the Cavendish Laboratory, at first by measurement of the distance they travel in a gas, using an ingenious method by which the precise *end* of the track of an alpha particle was recorded directly.

Three metal foils are placed parallel and close to each other. When a particle passes through the foils it ionises the gas and a minute electric current is produced which is amplified very greatly by means of valves. The three foils are however so connected to the amplifier that, when a particle passes through all three, then nothing is recorded. But when a particle passes into the space between the first and second but stops before it comes to the third, the valve amplifier responds and the particle is counted.

Quite recently a new magnet of ingenious design has been constructed by means of which it is possible to bend the alpha rays round into a semi-circular path of about 75 centimetres diameter. The particles are detected, not as in the method used by Rosenblum by their effect on a photographic plate, but by a similar amplification method to that already described.

By means of these methods, the structure of the complex groups of alpha particles emitted by various radioactive bodies has been analysed in great detail. From a knowledge of the energies of the various groups of particles it is possible to begin to learn something of the actual structure of the nuclei of heavy atoms, just as the study of the spectra of a molecule gives information about its electronic structure.

Amongst the many devices that have been invented to explore natural phenomena there is none which can so excite the sense of wonder as the cloud chamber. The final experimental result of most experiments consists in a set of figures, a graph, or a group of spectral lines on a photographic plate. Between the experimental result and the theoretical conclusion lie analytic steps, sometimes simple but often abstruse; without an understanding of these steps a full appreciation of the significance of an experiment is impossible. There is no such hindrance to the immediate appreciation of the beauty of the cloud method. A thousand repetitions will not tire the interest in the sight of the sudden flashing out on the black background of the bright trails that mark the tracks of single atomic particles. No two expansions are the same; each time one knows that one may see some new type of atomic event.

It can be said of most experimental methods that, if the discoverer had not discovered them, they surely would have been discovered very soon after by someone else. But if there had been no C. T. R. Wilson to begin experiments in 1896 on the formation of water drops in air and to achieve the first photographs of atomic tracks in 1911, physics might have lacked this superb experimental method for many years.

It is an astonishingly simple method. Air saturated with water vapour is contained in a flat chamber fitted with a movable piston. If the piston is suddenly lowered the air expands and so is cooled by the process of expansion; the now supersaturated water vapour condenses to form a cloud of water drops. It is on the detailed mechanism of this condensation of the water vapour to form drops that the possibility of photographing atomic tracks depends.

It had long been known that the pressure of water vapour which is in equilibrium with a convex water surface is greater than that which is in equilibrium with a flat surface. Now water will always evaporate from a water surface if the pressure of water vapour in the neighbourhood of the surface is less

than the equilibrium vapour pressure. Consequently a very small droplet of water would evaporate, on account of its convex surface, even if the surrounding gas is supersaturated to such an extent that condensation on a flat surface is taking place readily. Thus small droplets will not form at all unless there is some way of getting them through the early stage of their life when they are too minute to grow by themselves. This can be achieved in two ways. If a dust particle is present in the gas, it will form a nucleus on which condensation can occur, for even the smallest dust particle is so large from a molecular point of view that its surface is flat enough for condensation to occur easily on it. There is however another way of making the drops grow. If an ion, that is a molecule that carries an electric charge, is present in the moist gas, it can act as a nucleus for condensation. The charge on a minute droplet tends to make it grow in size just as a soap bubble expands if charged electrically, owing to the repulsion of the electric charges on its surface. In this way, every charged ion in a supersaturated vapour will have water condensed on it to form a visible droplet, even though no condensation at all is taking place in the rest of the gas. By finely adjusting the expansion due to the falling piston so as to obtain the correct degree of supersaturation, all the ions in the chamber can be revealed by the minute water drops that are formed on them. If there is only a single ion in each cubic centimetre of gas, that is, if there is only one charged molecule among 10^{19} uncharged ones, then each one can be revealed to the eye or photographed as a tiny brightly illuminated water drop.

Now when a rapidly moving electron or alpha particle passes through a gas it breaks up some of the molecules through which it passes into positive and negative ions. It leaves a trail of broken molecules behind it which after the expansion of the gas are revealed as a trail of water drops. If the particle is an electron moving very fast the ions are few and far apart so the track can be seen to consist of individual droplets. But if the particle is slower and carries a larger charge the ions are very numerous and the track appears quite continuous—a bright white line against the black background of the rest of the chamber. If the particle is deflected by collision with another atom the single trail of drops marking its original path divides into two, giving a forked track which marks the path of the two particles after the collision. From the measurements of such photographs the laws of interaction of atomic nuclei can be directly deduced.

The peculiar beauty of the cloud method is the direct visual acquaintance it gives with the details of atomic processes; without this method these processes would have become known, but by inference from a set of figures or from a graph; and before the method was known it would not have been reasonable to conjecture that such a direct acquaintance with atomic processes would ever be possible.

The cloud method has played an important part in the recent discovery of the neutron. Experiments carried out by electrical methods had led to the hypothesis of the existence of a new type of particle, able to pass through great thicknesses of matter without appreciable loss of energy and able to set other nuclei in violent motion by colliding with them. Cloud photographs confirmed this in a beautiful way. Short dense tracks appeared in the air, clearly due to the rapid motion of nitrogen nuclei. But of the track of the particle which had set them in motion there was no sign. Because the neutron has no charge it causes almost no ionisation and so its track is revealed by no trail of water drops. So the cloud chamber showed directly the existence of this new and most interesting type of particle.

The three methods of experimental physics that have been described as examples of experimental technique, the scintillation method, the amplification of ionisation currents by valves, and the cloud chamber, are as diverse as can be. The first depends on the odd properties of one particular crystal, just sufficiently impure, the second on the use of the highly specialised product of the radio industry, and the third on the fact that the vapour pressure of a liquid is greater over a

convex than over a flat surface. By such artifices as these does atomic physics progress.

III

Just as the progress of technique is continually opening up the possibility of new fields of research, so the development of theoretical physics both suggests new fields of enquiry and brings new relevance to old ones. However, the experimenter is always a specialist and does not often change his technique to follow the latest theoretical fashion. Often he cannot usefully do so, for there are few experiments which do not need a considerable apprenticeship. It is true that sometimes a single theoretical idea may lead an experimenter from one experimental technique to another. The belief in the essential unity of natural phenomena guided Faraday throughout a lifetime from discovery to discovery. But more often to-day an experimenter studies a technique for the sake of whatever results may emerge. He becomes expert in one or two techniques and he uses his skill in these to attack all such problems as may demand for their solution these particular methods. Laboratories themselves as well as experimenters are becoming highly specialised and this tendency will grow with the increasing cost of the equipment required to carry out the investigation of phenomena under special conditions of very high or low temperatures or high electric or magnetic fields.

Because an experimenter must specialise his technique he must also specialise to some extent his theoretical knowledge to cover that part of physics which is relevant to his experimental results. Within this field, he must follow the current developments of theoretical physics and, if he can, he must understand them. But the rapidly increasing abstractness of physical theory is making this more and more difficult. Even if a generation of experimenters should arise who have mastered non-Euclidean geometry in the schoolroom, it is not unlikely that they may find too late that theoretical physicists have changed their minds and have adopted some still more abstract method of describing nature. To-day an experimenter cannot always be expected to understand fully the theoretical implications of his work. It is not often that an experimenter is gifted enough as a mathematician to be able to read with profit the theory of the polarisation of electron beams, after an eight-hour day in the laboratory looking for a leak in the apparatus with which he is trying to discover if the theory is true. But luckily for the experimenter's pride there are still some parts of theoretical physics which he can understand. The reason why this should still be so, in spite of the highly abstract nature of the concepts of modern theory and of the high mathematical skill required to handle these concepts, is a matter of some interest.

Modern physical theory is abstract because it has been found that the world is not such a simple mechanical machine as was once believed. It is of course true that it is possible to put even the laws of classical mechanics into a very abstract form and it has, in fact, been found useful to do this for some purposes. To handle these laws in this form is certainly beyond the mathematical resources of most experimenters. It is not, however, usually necessary to do this in order to solve any but very complicated problems in dynamics. Actually it is not even necessary to solve the differential equations of motion in their simple Newtonian form in order to be able to predict the behaviour of, at any rate, simple mechanisms. For these dynamical laws are the laws of objects of everyday life. No one, in this mechanical and ball-playing age, can fail to have a wide practical knowledge of many of the important solutions of the differential equations of classical dynamics. The parabolic path of a projected tennis ball or the interchange between rotational and translationary forms of the energy of a yo-yo are matters of everyday knowledge. In addition, an engineer or physicist acquires by experiment and calculation an intimate knowledge of the exact behaviour of numerous types of mechanical systems. In order to obtain at least a qualitative knowledge of the behaviour of some machine, it is often not necessary to make any calculations at

all, for the processes occurring are of a familiar type, and by drawing intuitively on previous experience of such mechanical processes, it is possible to make the machine work in the mind, and to deduce immediately some, at least, of the desired results. This method of intuitive mechanical thinking, which is certainly a very complicated process involving a combination of abstract thinking with the use of visual and motor imagery, is of great importance both for the technical side of an experimenter's work, that is, for the design of his apparatus, and also for the theoretical side, that is, for the discussion and interpretation of his results. To design a complicated static apparatus requires a keen sense of the geometry of three dimensions; if the apparatus is a machine with moving parts, a mechanical sense is required in addition.

The possible ways of thinking about a simple problem of classical dynamics can be divided into two extreme types; the abstract mathematical method which studies the relevant solution of the differential equations of motion, and the intuitive methods of everyday life. Between these extremes lie the methods used by the experimental physicist. By the former method, a very few problems can be solved exactly; by the latter, a great number can be solved roughly; actually the experimental physicist, or engineer, usually starts by guessing intuitively the general type of the solution and then he proceeds to make the important details precise by the aid of simple calculations.

An exact mathematical solution of any problem in physics is never required, for the object of the solution is to compare it with measured quantities and these can never be exact. So even if a problem is solved by starting with the equation of motion in its most general form, suitable approximations are always allowable, and, in fact, are almost always necessary in order to obtain a solution at all. To know where and what approximations to make is to have overcome half the difficulties. It is here that the intuitive judgment of the experimenter is valuable, for he has a practical knowledge of the orders of magnitude of the various factors involved and so can judge immediately which have to be taken into account and which can be neglected.

This same geometrical and mechanical sense is equally necessary for the theoretical discussion of experimental results, because all theories of, say, atomic and molecular structure, are in part mechanical too, since the aim of physics has inevitably been to attempt to explain the microscopic structure of matter by the familiar concepts derived from matter on a large scale. Before the advent of the Quantum Theory it was possible to believe that the material world might be explained entirely in these terms. Indeed, the practical temperament of some physicists, particularly in England, gave their mode of thinking such a bias towards mechanical interpretations that they were unwilling to admit of the possibility of other methods. For if the microscopic world of atoms had been found to obey the same laws as the macroscopic world of everyday objects then it would have been possible to understand the world in the same sense that it is possible to understand the working of a motor car. Even if the atomic laws were not quite the same, provided at least that atoms consisted of particles moving continuously in space, then a visualisable model of an atom could still be constructed, even though the particles did not interact according to Newton's laws.

Now that modern theoretical physics has been forced to abandon a description of atomic phenomena in terms of the continuous motion of particles in space, it is no longer possible to retain a purely mechanical model of an atom. But, luckily for the unmathematical, it has proved possible to retain some features of the mechanical model and so to retain to some extent the possibility of this invaluable type of semi-visual thought. This is a matter of the highest importance, for a *physical* as opposed to a *mathematical* discussion of a physical problem would be almost impossible without the use of some form of model. It is, in fact, almost impossible to discuss general relativity theory except purely mathematically for no models applicable to the case exist. It is interesting therefore to consider how such models of some of the very abstract modern theories of physics can be made, and what relation these models have to the abstract theory. If it is possible to invent such models, then the experimenter can continue to think "physically" about his results; he can predict the kind of atomic phenomena which will happen in certain circumstances, and so he can plan experiments and appreciate the significance of their results. Failing such models he must hand over half his job, and that the most fascinating to his intellect, to the mathematical physicist.

Now the Quantum Theory shows clearly that no model, that is, no model which, in Kelvin's phrase, is mechanical all the way through, can represent the behaviour of an atom. But it must be noticed that Bohr's original theory of atomic structure, on which all subsequent theories have been built, did allow some degree of visualisation, that is to say, an atom could be thought about in a qualitative way, and qualitative deductions could be made, by using the half-mechanical and half-symbolic picture provided by the theory. The model was partly mechanical, but it was not "mechanical all the way through". Electrons were pictured revolving round an atomic nucleus in definite orbits to be calculated according to classical mechanics, but the transitions between orbits could not be expressed mechanically, but had to be described symbolically. Of course, Bohr's theory was not of the extreme abstract type of modern Quantum Mechanics. It represented a supreme inductive step from classical mechanics, with its possibility of direct visualisation, to the new abstract theory with its essentially symbolic character, and it possessed some of the qualities of both. It has already enabled nearly a generation of physicists to think "atomically" with astonishing success—and without advanced mathematics. Through its simplicity, it became part of the laboratory equipment of the experimental worker.

Though many of the logical difficulties inherent in Bohr's theory have been clarified by the later developments of the wave mechanics which followed from it, the characteristic type of physical thinking to which physicists were introduced by this model of the atom is still of the utmost importance, at any rate to an experimenter.

It is possible to imagine that Schrödinger's wave mechanics might have been discovered before and not after Bohr's theory. Then it still would have been necessary to deduce Bohr's theory from it, in order to facilitate physical thought. For instance, the deduction from Schrödinger's theory of the energy levels of the hydrogen atom requires the finding of the characteristic values of a solution of a wave equation in three dimensions. By Bohr's theory they can be deduced in a few lines of simple algebra.

A half-mechanical and half-symbolic model of the type of the Bohr model has a threefold relation to the more abstract and complete theory. It permits the physicist to think physically instead of only mathematically; it acts as a short cut to certain of the precise results predicted by the exact theory, and it may also enable approximate solutions to be found to problems which are so complex as to be beyond exact solution.

An illuminating example illustrating these considerations is the vector model of the spectroscopist. The general solution of the wave equation for an atom or molecule with many electrons has never been obtained, and even if it had, the mathematics would be far beyond the comprehension of the experimenters who are engaged in finding order in their complex spectra. Though a complete solution is required to predict the actual position of the lines, the general nature of the spectral series and their mutual relations has been proved to depend primarily on the way that the angular momenta of the various electrons combine together in the complete atom. Now certain simple rules for this have been deduced from the general theory, and those rules can be put in a simple semi-geometrical form. The momenta are to be treated as vectors and added, like displacements, according to the parallelogram law, but in the answer—so the curious rule runs—whenever such a quantity as j^2 occurs it must be replaced by

$j(j+1)$. So provided this queer change is made in the answer, the momenta of the various electrons can be considered as combining mechanically. Though sometimes the method breaks down, and the spectroscopist must learn when to expect this, the vector model is indispensable to the practical spectroscopist. As a source of information about the spectra of atoms it is imperfect in the same sense that a torn copy of an out-of-date Bradshaw is imperfect. It gives some information correctly, some incorrectly and some not at all.

To illustrate the use of a semi-visualisable model to solve problems approximately which cannot be solved at all exactly, no better example can be found than that of Fresnel's construction for treating of the propagation of light. It is believed that the propagation of light is governed exactly by Maxwell's equations for the electro-magnetic field. But of the cases of interest in optical theory, which is mainly concerned with the diffraction of light by screens and apertures, only very few exceedingly simplified cases have been solved rigorously. Yet almost the whole field of practical optics can be handled by use of Fresnel's construction. Each point on any wave-front is considered as the source of a secondary wavelet, which starts out with a phase a quarter of a period ahead of the incident wave. Then the form of the wave farther on can be found by adding up the effects of all the secondary wavelets. These simple rules allow the optical worker to solve very simply almost all his problems. The relation between Fresnel's construction and the exact theory of the propagation of waves is clear. It is a brilliant method of solving approximately the equation of wave propagation. Formerly it was not always recognised as such, but was considered to represent a more or less exact description of the actual behaviour of the medium in which the vibration of light took place. Though this view can hardly now be maintained, Fresnel's construction, which historically was a discovery of the highest importance, must be recognised as being a wonderful "model" of the propagation of light, in the sense of this discussion; that is, it permits "thinking physically" and it permits the actual solution of almost all the important optical problems.

Now the simpler properties of wave motions become familiar to any observant person through direct experience of the waves on the surface of water. The physicist acquires a more detailed knowledge of wave motions by means of laboratory experiments with ripples on liquids and by the study of the propagation of light and sound. He uses Fresnel's construction, which is equally applicable to all kinds of waves, to understand the finer details of these phenomena. In this way he acquires a wide and intimate knowledge of the properties of many kinds of wave motions, so that he can solve intuitively simple problems concerning waves, just as he can solve simple mechanical problems concerning particles. But the most familiar waves, those on the surface of a liquid, are themselves complicated mechanical processes, so that when the propagation of light is visualised by means of a wave picture, it is really a very complicated mechanical picture which is being used. The explanation of a phenomenon in terms of waves is therefore not fundamentally different from an explanation in terms of particles. The difference is only that practical experience of wave motions makes the experimenter so familiar with this special type of complicated mechanical motion called a wave, that he can skip the mechanical steps and appreciate the motion as a whole.

It has followed from this that the propagation of waves has come to rank with motion of particles as an intuitive method of representing and understanding nature. In this way, waves and particles have become the conceptual bricks out of which the somewhat jerry-built structure of intuitive physical knowledge can be built on the foundations of practical experiment and abstract theory. Formerly the conception of waves and particles had distinct fields of use, the first to explain light, the second matter. Now that light is found to have particle properties and matter wave properties, the two pictures are used side by side as a method for the intuitive

discussion of both radiation and matter. The physicist must learn when to use one picture and when the other, but if he learns this, if, that is, he grasps something of Heisenberg's uncertainty principle and of Bohr's subtle complementary relations between the wave and the particle pictures, and between both these and the abstract theory, then he can still think physically though he cannot multiply matrices.

With such mental tools as these must the experimental physicist go about his work in the laboratory. He must visualise an alpha particle moving in a hyperbolic orbit round an atomic nucleus, but he must know just at what speed the alpha particle ceases to behave like a particle and becomes, for a time, a wave, to recover its particle properties in time to make a bright scintillation on a screen. He must know that when two exactly similar particles collide, the queerest things happen, to be understood neither by waves nor particles, unless the experimenter is prepared to follow these concepts into six dimensional space. He must also learn how to use his knowledge of waves to let particles slip freely through a "potential barrier", that is, a region where their kinetic energy would be negative; he must also know that there are no rules against the overcrowding of alpha particles, but that electrons can be housed only in pairs.

To plan or interpret an experiment he must thus have at his command a number of theoretical principles, just as to do the experiment he must master a number of techniques. With his knowledge of thermodynamics to keep him from gross error and his knowledge of classical mechanics to tell him what happens in the limiting case of large quantum numbers, he can use these various models and rules to carry on a type of physical thinking, which, though tentative and approximate, is quite indispensable.

With such varied manual and mental skills as have been described does the experimenter go about his work in the laboratory, an amateur in each alone, but unique in commanding them all.

It is the intimate relation between these activities of hand

and mind, which gives to the craft of the experimenter its peculiar charm. It is difficult to find in other professions such a happy mixture of both activities. Few people are content with an occupation whose only manual element is the handling of a pen or a typewriter. Yet many, who embark on the career of an engineer from love of using tools, find later on that their main activity is as sedentary as that of a bank clerk. A common reaction to the fact that the office worker is, with some notable exceptions, paid more than the skilled mechanic, is to embrace, when possible, the career of the former while adopting some practical hobby to offset the loss of the satisfaction to be derived from the latter. The experimental physicist is luckier; his legitimate field of activity ranges from carpentering to quantum mechanics; it is his job both to make and to think, and he can divide his time as he thinks fit between both these pleasurable occupations.

CHEMISTRY

By C. P. SNOW

I

CHEMISTRY is essentially the science of molecules. If we take a piece of any substance and subdivide and subdivide, we arrive in the end at small particles beyond which division cannot go. That is, these small particles are really pieces of the original substance; but if we divide any more, we shall produce something which is different from the original substance. The small particles are *molecules*. They consist of two or more atoms attached together. An atom of hydrogen and an atom of chlorine attached together in a special way form a molecule of hydrogen chloride, which, of course, is different in properties from the two atoms which compose it.

Modern physics has told us a great deal about the nature of atoms. Since atoms are the bricks from which molecules are built, this physical knowledge is the starting-point for chemistry, which is concerned with the molecules when formed. An atom consists of a *nucleus* which carries a positive electric charge and which contains almost all the *weight* of the atom; around the nucleus *electrons* (units of negative electricity) move in a way which may be compared to the solar system. It is not ultimately correct to do so; but the comparison is good enough for the purposes of chemical description; and it is difficult to follow present-day physical ideas unless one first knows this picturesque conception of the atom.

The nucleus takes the place of the sun, the electrons circulate round the nucleus in paths at various distances from it, just as the planets move round the sun. Some electrons keep very close to the nucleus, just as Mercury keeps close to the sun; others sweep out longer paths, like Neptune or Pluto. The accurate description of the nucleus and elec-