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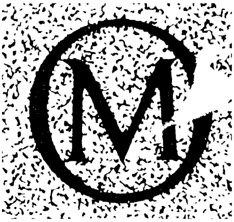

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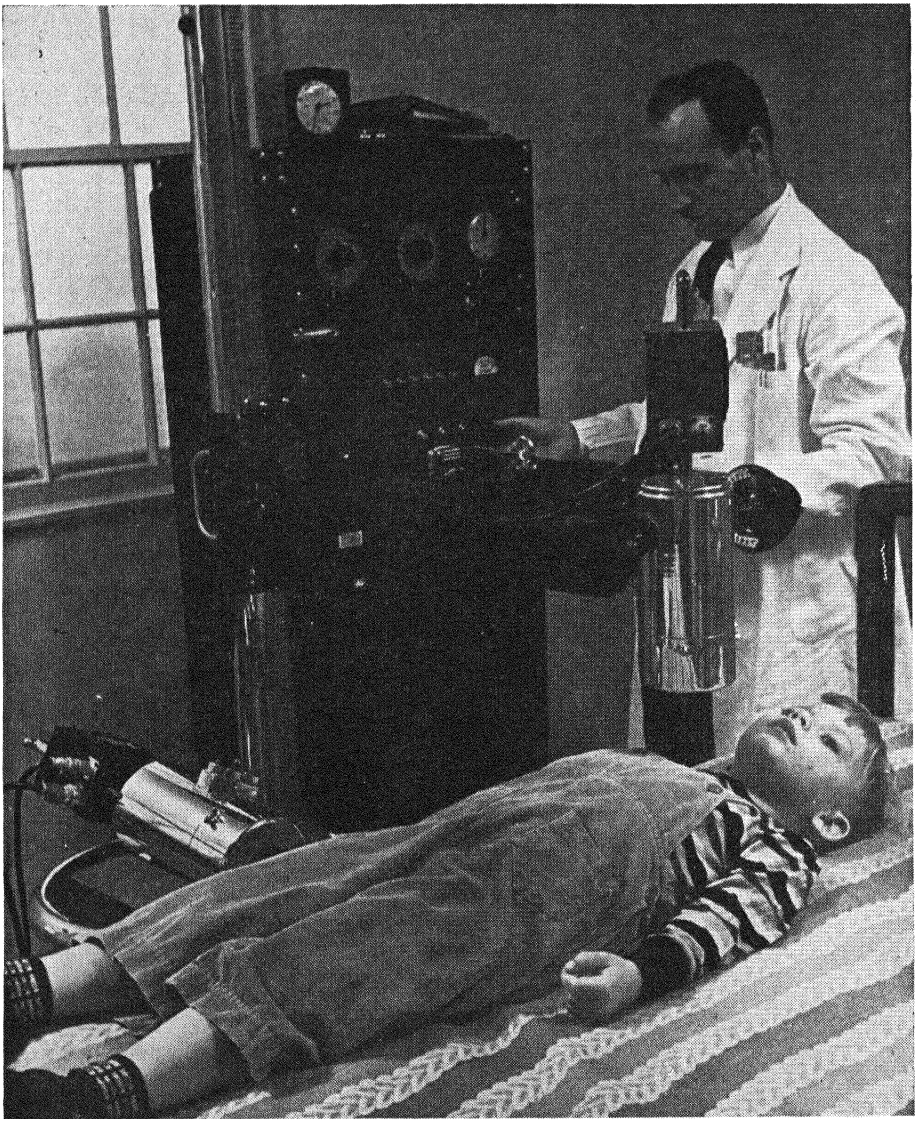

ATOMIC ENERGY CAN SAVE LIVES

The boy has been dosed with radio-active iodine and his thyroid gland is now being tested

METHUEN'S OUTLINES

ATOMS AND ENERGY

by

F. R. ELWELL

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First published 1958

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PART II: ATOMS IN THE SERVICE OF MAN

sulphur (you probably know what sulphur looks like—in the form of 'flowers of sulphur' it is sometimes used by gardeners as a fungicide) and a bottle of oxygen. But he could not split the calcium into simpler chemicals than calcium, nor the sulphur, nor the oxygen. These things are elements, the simplest possible chemical substances, and there are about ninety different ones found naturally in the world.

One of the reasons why many scientists think that the Earth and the Sun were once part of the same mass of matter is because a great number of the elements we can find on the Earth are known to exist on the Sun as well. We can tell this because each different element when it is heated to a very high temperature glows with coloured light of its own special wavelengths. If you put a pinch of salt on the fire at home you get a bright yellow glow. This is the particular glow of the element sodium in the salt. A chemist can't take a bit of the Sun and analyse it to find out if sodium is there; but he can examine the light that comes from the Sun, and he finds that the Sun is, in fact, giving out light rays of exactly the same wavelength as heated sodium, so he concludes that the Sun must contain sodium.

So far, about sixty of the ninety-odd elements known on the Earth have been detected in the Sun by this means, and now that we are able to send up instruments above the atmosphere (which absorbs quite a lot of the Sun's ultraviolet radiation) there is a very good chance that we shall be able to detect most of the others.

So the Earth and, most probably, the Sun and all the other planets are made up of about ninety different simple substances we call elements.

WHAT IS AN ATOM?

Now suppose we take a lump of one of those elements—copper, shall we say. We'll suppose that it is pure copper—there is no trace of any zinc or any other element mixed up with it. We could cut that lump into two pieces, and they would both still be pure copper. Suppose we go on cutting and cutting and cutting. Our pieces of copper would get smaller and smaller and smaller, and sooner or later they would be such tiny specks that we could scarcely see them. But suppose we were endowed with very keen sight, and suppose we had extremely fine instruments, we could imagine ourselves able to go on cutting our piece of copper into smaller and smaller pieces until at last we should come to a very tiny piece indeed which we could no longer cut in two. This is the smallest possible part of the element that can exist. We call it an *atom.*

At one time scientists thought that atoms were the smallest thing possible. They certainly are the smallest possible parts of the various elements. But scientists have found ways of breaking up certain atoms into even smaller pieces. But when they do this the pieces are no longer atoms of their original elements. Which means, in fact, that what we said about elements being unchangeable is no longer quite true. It now *is* possible to break up some of the elements found in nature into rather simpler things—but not by the ordinary processes of a chemical laboratory, such as heating them with other chemicals, or passing electricity through them. Smashing atoms is a difficult and dangerous business, and it needs very different apparatus from the bunsen burners and the flasks and test-tubes we think of as belonging to the chemist's laboratory.

But before we explore the inside of an atom let's have a look at some of the things that atoms will do.

ATOMS AND MOLECULES

Most kinds of atom—not quite all—have the ability to seize hold of other atoms and form the tight little groups we call *molecules*. Atoms of the element oxygen, for example, don't usually wander around in the air all by themselves. They go about in pairs. And the two atoms of each pair are very tightly joined together. These small particles, the little groups of atoms which waltz around in the air we breathe, are molecules.

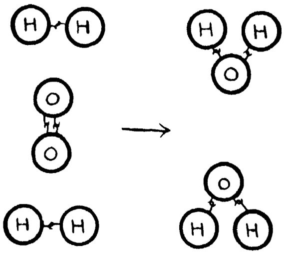
A *molecule* of oxygen contains two *atoms* of oxygen, firmly joined together.

Another very important element is the gas hydrogen. Hydrogen is not found as a free element in the air as oxygen is, but it is quite easy to make.

Hyrogen atoms, like those of oxygen, go around in pairs. One hydrogen molecule contains two hydrogen atoms, firmly joined together.

Suppose you were to have a bottle containing a mixture of oxygen and hydrogen—twice as many hydrogen molecules as oxygen molecules. Now suppose you put a match to the mixture. What happens? A loud explosion. The atoms in the molecules of oxygen come unstuck from each other, and the atoms in the molecules of hydrogen come unstuck from each other, and each atom of oxygen seizes not just one, but *two* atoms of hydrogen, and away they fly, whizzing around inside the bottle as a little molecule of water vapour. H_2O, in other words. If you are a chemist, you represent the explosion in this way:—
$2H_2 + O_2 \quad 2H_2O$.

And if you're not a chemist, you can show it like this:—



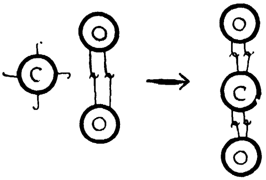
$2H_2 + O_2 = 2H_2O$

Now let us think about another common element, carbon. Carbon is the stuff that soot is mostly made of, and another kind of carbon called graphite is used for the long black 'lead' inside your lead pencil. A third kind is the beautiful colourless diamond. Although these three look so different from each other they are all, in fact, forms of the same element, carbon.

An atom of carbon can seize hold of four atoms of hydrogen to make a molecule which chemists write as CH_4. Its chemical name is methane, and it is the gas known as marsh gas which rises up as bubbles when you stir a rather stagnant boggy pond with a long stick.

The carbon atom will also join itself very readily to two atoms of oxygen. This is exactly what happens when you burn a piece of coal. Each atom of carbon in the coal joins on to two atoms of oxygen from the air, and a new molecule, carbon dioxide—CO_2—is formed.

$$C+O_2=CO_2$$

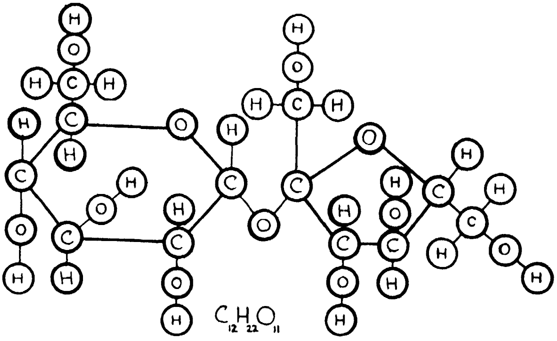


$C + O_2 = CO_2$

A few of the elements—things like argon and neon, which are two of the gases in the air (neon is the gas used inside neon lamps)—refuse absolutely to join up with any other elements. And their atoms always go about singly, not in pairs like the atoms of hydrogen and oxygen. An argon atom—or a neon atom—is quite incapable of joining on to anything—its own kind of atom or any other.

Most kinds of atom seem to prefer being attached to atoms not of their own kind but of other kinds of elements; this means that only a few of the elements are found in a pure state in nature. Just occasionally you might come across a little nugget of pure gold, and there are places where deposits of certain other metallic elements are found. A few of the non-metallic elements, too, are also sometimes found in an uncombined state in the earth—sulphur, for example. But, by and large, most elements in nature are found combined with other elements as *compounds*. And the atoms of the different elements are always joined together in definite little groups as molecules.

Common salt is a compound; one atom of sodium joined to one atom of chlorine makes one molecule of sodium chloride, which is the chemical name for common salt. Ordinary cane sugar is another; this is a much more complicated compound with numerous atoms all strung together like rows of children holding hands. A molecule of this kind of sugar contains twelve atoms of carbon, eleven of oxygen, and no less than twenty-two atoms of hydrogen. They are joined together like this:—



$C_{12}H_{22}O_{11}$

One way of spelling 'sugar'

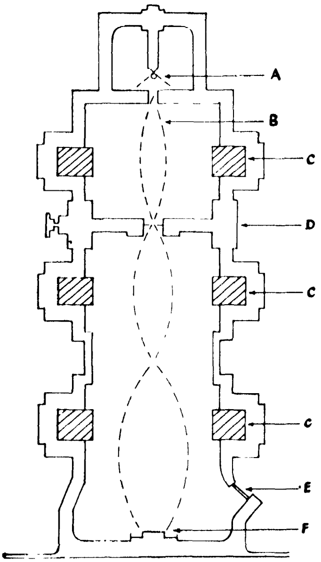
This is a complicated molecule, but there are many others a lot more complicated than that—some of them even run to hundreds of atoms.

Although there are only just over ninety elements found naturally in the world there are thousands and thousands of different possible compounds.

A peculiar thing about compounds is that they are not at all like the separate elements from which they are composed. Sugar isn't a bit like carbon or hydrogen or oxygen. Salt isn't a bit like sodium (which is a soft silvery metal) or chlorine (which is a green poisonous gas). The world we live in, though containing so few chemical elements, has an enormous variety of compounds—mountains and lakes and woods and fields and men and horses and ants are all formed of chemical compounds—of atoms combined together in thousands of different ways to make thousands of different kinds of molecule.

Atoms are very tiny things. The ink in which this book is printed consists largely of carbon, and in the single fullstop at the end of this sentence, there are probably somewhere in the region of 100,000,000,000,000,000 carbon atoms. If you could imagine a magnifying glass of such intense power that it could enlarge a single carbon atom to the size of a small mouse, then a real mouse, looked at through the same glass, would be magnified to the size of the whole Earth.

In fact, no magnifying glass is powerful enough to see an atom. Even a compound microscope with the most powerful combination of lenses in the world is not powerful enough to show objects as tiny as that, for the light rays by which we see things have a wave-length more than a thousand times the width of an average sized atom, which means that rays of light cannot be reflected from single atoms as they can from larger sized objects. There is, however, another kind of microscope, the electron microscope, which can show molecules and even single atoms, but this works on a completely different principle.



How an electron microscope works. The filament, A, produces streams of electrons, some of which pass through the small aperture as a divergent beam, B. They are focused by the electromagnets, C, and pass through the specimen in its holder, D. More electromagnets re-focus the beam so that a greatly enlarged image is thrown on the fluorescent screen, F. This image is viewed through the window, E.

THE BROWNIAN MOVEMENT

But if we cannot see actual atoms and

molecules through an ordinary microscope we can see a rather strange thing which tells us something about the way these tiny specks of matter behave.

If we mix a little very finely ground powder with water—some of the pigments used for making ordinary water colour paints do very well for this—and put a drop on a slip of glass and look at it under a microscope we see, as we expect, the tiny particles of powder suspended in the water. Now however careful we are to make sure that the microscope is absolutely steady and that we are not disturbing the drop of water in any way, for example, by breathing on to it, the little particles suspended in the water are never absolutely still. They dance about apparently quite at random, almost as if they were being bombarded from various directions by invisible bullets. In fact, that is exactly what is happening to them —they *are* being bombarded by invisible bullets. The bullets are the separate molecules of water which are themselves always in ceaseless agitation. These molecules are far too small to be seen. But their effect on the much larger paint particles can be seen quite easily.

This peculiar movement of small particles suspended in water was first noticed by the botanist Brown more than a hundred years ago and was called after him the Brownian movement. But it wasn't until the end of the last century that its cause was realized, and that the fact that molecules of matter are in constant motion began to be understood.

STATES OF MATTER

There are three states in which matter can exist. Iron and salt and gold and sugar are all *solids*. Oil and alcohol and mercury and water are *liquids*. Hydrogen and oxygen and nitrogen and carbon dioxide are *gases*.

If we take some liquid water and cool it enough we get ice, which is solid.

If we take some liquid water and heat it enough we get water vapour, which is a gas.

So water can exist in three states, solid, liquid, and gas.

The molecules of water have two distinct and opposite tendencies. One is that they attract each other and tend to stick together; the other is that they repel each other and tend to fly apart. Which tendency wins—whether the molecules adhere together as solid ice, or whether they are completely free of each other as water vapour—depends on the amount of energy they are given.

The molecules are always in constant agitation, and it is this agitation which tends to push them apart, like a crowd of people jostling each other at a football match. The hotter the molecules are, the more agitated they get. If they are cold, they move less freely, and the attractive force wins; very cold water molecules adhere closely to each other to form solid ice. But the more they are heated the faster they move. If you heat ice, there comes a point when the heat energy you give the molecules is sufficient to overcome much of the attraction that they may have for each other, and instead of adhering together as a solid mass they break away from each other and move freely about as liquid water.

While in the liquid state the molecules of water still have a considerable attraction for each other, and this is particularly noticeable at the surface of the liquid. The molecules at the surface form a kind of skin which is strong enough to support the weight of small insects, and on which, if you are careful, you can even float a steel needle. Even so, some of the molecules in the bulk of the liquid which have more than the average amount of energy sometimes break through the surface film and escape in the air as particles of water vapour. When this happens we say that the water is evaporating. We can speed up evaporation by heating the water, so giving the molecules more energy and making them vibrate more strongly. There finally comes a point at which all the molecules have so much energy that they break away freely from the bulk of the water and escape as a gas. At this point the water is boiling.

If we now collect all the water vapour formed from the boiling water without compressing it in any way we find that it takes up considerably more room than the water from which it came, for the separate molecules are vibrating so strongly that each one occupies an effective space many times the size of the molecule itself. Imagine a number of people waltzing in a crowded group in the middle of a large ballroom. They move round rather slowly, but even so they occasionally jostle their neighbours. Now imagine that each couple begins to jive with a great deal of energy. Everyone will be jostled far more by his neighbours, and the dancers will spread themselves out until the outside ones are jostled against the wall. If the doors are open, some of the dancers may even be pushed outside, but once outside they have plenty of room for jiving, and are much less likely to collide with other dancers. But if you incautiously come too near to the dancers, you may well be kicked, for the person dancing energetically occupies a good deal more space than if he were standing still, or even dancing rather slowly.

So it is that molecules of a gas take up more room than the same molecules when they are a liquid; they are whizzing about far more vigorously, and although there is quite a lot of space between them they frequently collide with each other; they also bombard the walls of the vessel containing them all the time.

If you blow up a toy balloon the balloon feels hard, though you know very well that the air inside is not hard, and neither is the rubber from which the balloon is made. But the balloon *feels* hard because the molecules of air are forcibly compressed, and they therefore push hard against the rubber as they try to expand. When you hold the balloon between your two hands you are feeling, not hard rubber, but the pressure of the air molecules inside as they bombard the wall of the balloon.

The air molecules around us are constantly bombarding us—they exert a pressure on our skins of fifteen pounds on each square inch. That sounds quite a lot, but we are used to it. In fact, the molecules of liquid inside our bodies are also exerting a pressure outwards, and if the air pressure balancing this were suddenly removed we should burst.

ABSOLUTE ZERO

Molecules, then, are always moving. They move because they possess energy. The hotter you make them, the more energy they have, and the faster they move. There is, in theory at any rate, no limit to the amount of heat you could give them; the atoms inside the sun are at a temperature of twenty million degrees centigrade. The molecules of a gas have more energy than the molecules of a liquid, and these in their turn have more energy than the molecules of a solid. If you cool down a solid—if you take away *all* its heat—the molecules will slow down and finally stop moving altogether. This is the coldest temperature possible—we call it Absolute Zero. It is approximately 273 degrees below the freezing point of water. Not, you may think, an impossibly low temperature; certainly not as difficult to imagine as twenty million degrees *above* freezing point.

Yet try as they will, scientists will probably never be able to make anything quite as cold as this. They have got very close to Absolute Zero—to within one ten-thousandth of a degree of it, in fact, but right down at the bottom atomic movement stops altogether, and that is something we have not yet learned how to bring about.

All matter, then, consists of atoms, or little groups of two or more atoms tightly joined together to form molecules.

Molecules and atoms all possess energy, and the energy makes them vibrate. The more energy they have the hotter they get and the more they vibrate. If they are made hot enough solid elements become first liquids and then gases, and inside the Sun the temperature is so high that they are all in the gaseous state, even though they are very tightly packed together. (The pressure inside the Sun is terrific; if it were possible for you to live in the centre of the Sun the pressure on your body would be forty thousand ***million*** times greater than it is on our Earth.)

The atoms in the sun possess tremendous energy. Yet they are losing heat all the time, for heat is continually being poured out into space in the form of radiation.

So why does the Sun remain hot?

The answer is another source of energy altogether—not the energy given out as an atom vibrates—but the energy that holds the middle part, or *nucleus*, of the atom together: *nuclear energy*.

ELECTRONS, PROTONS, AND NEUTRONS

Let us now take a look inside an atom.

We can't really do this, of course, but scientists have been able to calculate not only how big, or how small, atoms are, but how they are made up. It is important to remember that the picture we shall see of the interior of the atom is based on indirect evidence; from the way the atom behaves we work out how it is put together. There are, in fact, two ways of regarding atoms. One is to think of them in terms of mathematical formulæ which seem to explain their behaviour; this method is far too difficult for a book of this kind, and many scientists are not very happy about it, either. The other way is to picture little models of the atoms, and this is what we shall do; remember, however, that our models may not be complete ones.

We begin with a very large model.

Imagine yourself standing in the middle of a field whizzing a piece of rope with a stone on the end rapidly round and round your head. It would, you will agree, be dangerous for anyone to approach you nearer than the length of this rope—they would certainly be hit by the whirling stone. If the rope were five feet long, for example, you would be occupying, for all practical purposes, a circular patch in the middle of the field ten feet across, though the solid bit in the middle of that patch—you—would be very much smaller than this.

You and the whirling stone represent an atom—a very simple atom, the simplest there is: an atom of hydrogen.

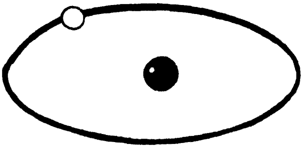


Diagram of a Hydrogen atom

The main part of the hydrogen atom consists of a fairly solid lump in the middle called a *proton*; the proton has a positive charge of electricity. Circling round the proton, some distance away from it, is a much smaller particle, an *electron*; this has a negative charge of electricity. The atom as a whole has no charge, it is neutral. The positive charge of the proton is exactly balanced by the negative charge of the electron. The electron's weight is very small compared with the proton's.

The hydrogen atom is not only the smallest atom possible; it is also the only kind that contains just those two sorts of particle. All other atoms contain, besides positive protons and negative electrons, a third kind of particle which has no electric charge. This neutral particle is called a ***neutron***. The neutrons are practically the same size and weight as protons—they can be thought of as protons without a positive charge. All the protons and neutrons in an atom are bunched together tightly in the middle; they make up what we call the ***nucleus***. When a large atom is split up into smaller pieces some of the energy binding the protons and neutrons together is released. This ***nuclear energy*** can be harnessed to perform useful work; it can also be suddenly unleashed on a large scale in frightful weapons of war.

ISOTOPES OF HYDROGEN

At one time it was thought that all the atoms of one particular element must be exactly alike. It is true that they all have the same number and arrangement of electrons revolving round the nucleus. And they all behave in the same way when they unite with the atoms of other elements to form chemical compounds. But we now know that the nucleus of one atom of an element may not be *exactly* the same as the nucleus of another atom of the same element. It may be a little heavier or a little lighter.

Take the simplest element, hydrogen, as an example.

The usual kind of hydrogen atom contains, as we have said, one proton as its nucleus and one electron, revolving around this. But there is another kind of hydrogen known as deuterium, or heavy hydrogen. In addition to the proton in its nucleus it also contains a neutron. It still

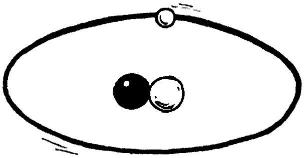


Diagram of a Deuterium atom

has just the one electron, and it still behaves like ordinary hydrogen in the way that it combines with other atoms—for example, in combining with oxygen to form water. But as its nucleus contains exactly twice as many particles as the ordinary hydrogen atom, the deuterium atom is twice as heavy as the ordinary kind. It is useful to be able to compare weights of atoms; if we call the *atomic weight* of the simplest kind of hydrogen atom 1, the deuterium will have an atomic weight of 2. The amount of deuterium in ordinary hydrogen is very small —only about one part in six thousand; but if you think of the vast amount of hydrogen combined with oxygen in the water of the sea, even one part in six thousand adds up to quite a lot. We shall be meeting deuterium again later on.

Fairly recently a third kind of hydrogen atom has been discovered. This is known as tritium, and its nucleus contains two neutrons in addition to the single proton.

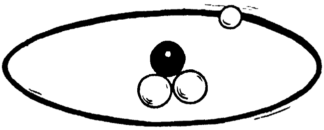


Diagram of a Tritium atom

There is, of course, still just the one electron whose negative charge balances the positive charge of the proton. Tritium has an atomic weight of 3.

These various forms of the one element hydrogen are known as *isotopes.* The isotopes of an ordinary element differ from each other only in their atomic weights—in the presence or absence of one or more extra neutrons in the nucleus.

SHELLS OF ELECTRONS

After tritium the next heaviest kind of atom, with an atomic weight of 4, is the helium atom. It contains four particles in the nucleus, two neutrons and two protons. And since the positive charges of the protons must always be balanced by the negative charges of the electrons revolving around the nucleus, it follows that the helium atom must have two electrons.

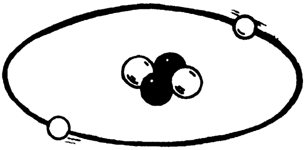


Diagram of a Helium atom

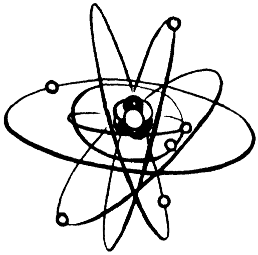
Helium is a gas—an *inert* gas: it is unable to combine with any other element. Atoms can only attach themselves to other atoms if there is a space, as it were, in the shell occupied by the outermost electrons. The shell of the hydrogen atom, containing one single revolving electron, is not complete. There is room for another electron, shared with the outside shell of another atom. This is why hydrogen combines very readily with practically every other element. But with helium it is different. The outside shell already contains two whirling electrons. There is a 'House Full' notice up—no room for any more electrons from outside. So the atoms of helium always remain single.

With larger and heavier elements there are more and more shells of electrons round the central nucleus. You can think of them rather like the skins of an onion.

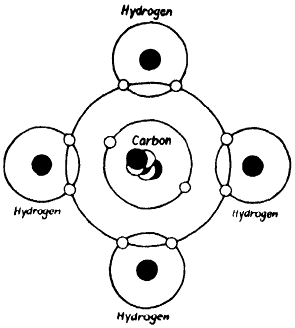
The innermost shell is full up when it contains two electrons. But the outer shells can each hold up to eight electrons altogether. If the outermost shell is already full, the element is bound to be inert—it can combine with no other element. Examples of inert elements are helium, neon, argon, krypton, and xenon.

In most elements there are spaces in the outside shell of electrons, and this means that electrons from the outside shell of other atoms can be shared.

In an ordinary carbon atom there are two shells of electrons. The inside one contains, of course, two electrons. The outer one contains four—which means that it is only half complete. Six electrons altogether—therefore, balancing the six negative charges, there must be six positively charged *protons* in the nucleus. In addition to these six protons the carbon nucleus also contains six neutrons. So, with twelve nuclear particles altogether, the ordinary carbon atom must have an atomic weight of 12. About one in a hundred carbon atoms, however, have an extra neutron in the nucleus; the atomic weight of this isotope of carbon is therefore 13. There is yet another isotope, Carbon-14, which we shall meet later on.



Digram of a Carbon atom



Electronic structure of CH_4

ELECTRONS AND LIGHT

Every electron revolving around the nucleus of an atom has its own particular orbit, just as each of the planets revolving round the sun has its own special path. But the electrons don't necessarily remain fixed in these orbits as the planets do in theirs. The Earth moves round the sun along an elliptical path—almost a circle—and, fortunately for us, it always stays in that path. It doesn't suddenly leap across space and then settle down for a spin or two near Mars or Venus. Yet this is the sort of things electrons can do, especially those in the outermost orbits of an atom. Sometimes such an electron leaps into a 'spare' orbit, as it were; this may happen if the atom is heated or if it is bombarded by a stream of electrons from outside. The atom is then in what we may call an 'excited' state. Sooner or later the electron will leap back again into its former orbit, or perhaps into a different orbit altogether. When this happens the atom gives out energy in the form of heat or light, and the wavelength of this light depends on relative positions of the two orbits. One electron making one jump gives out one tiny parcel of energy of one particular frequency. But there are several ways in which electrons in the atoms of the same element can jump. And if a lot of electrons in a lot of atoms are all hopping about, the element as a whole will be giving out a continuous stream of light made up of a number of different wavelengths. The particular combination of wavelengths makes up the *spectrum* of that particular element. And from the spectrum scientists can tell which element is giving out the light. This is, in fact, how we know which elements are present in the sun.

Sometimes the electrons of the inside shells can be made to change their orbits. If this happens the energy charge as they jump back again is so great that very high frequency rays—X-rays—are produced. We come back to those on page 19.

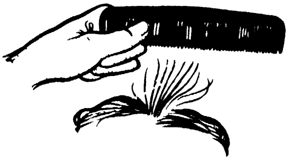
ELECTRONS AND ELECTRICITY

Sometimes the electrons in the outer shell of an atom may be stripped off from the atom altogether. When this happens the rest of the atom is left with a positive charge, for the protons in the middle are not now completely balanced electrically by an equivalent number of electrons. We say that the atoms have become *ionised.*

The same sort of thing can happen to groups of atoms; one group may lose an electron, or several electrons, and so become a positively charged *ion*; another group may gain electrons and so become a negatively charged ion.

Occasionally the outside electrons of atoms can be made to come apart from their atoms simply by rubbing them. If you rub your plastic pen-holder on the woollen sleeve of your jersey or jacket you give it an electric charge; you can show this by making it pick up tiny pieces of tissue paper.

The same sort of thing happens when you run a comb through your hair; you give both the hair and the comb an electric charge, and you have probably often noticed how the individual hairs may stand apart from each other, and how they can be made to bow and bend in the direction of the comb when it is brought near them. The explanation is simple. The rubbing transfers some of the electrons from the atoms in the comb on to your hair. Each hair, with its layer of extra electrons, then has a negative charge. Since negative charges repel each other the individual hairs tend to push each other away—in other words they 'bristle' or 'stand on end'. But the atoms in the comb have lost some of their electrons; they are left with a lot of positively charged protons, now not balanced by an equivalent number of electrons. The comb as a whole now has a positive charge, and when it is brought near to the hairs it attacts them.



Much the same sort of thing happens when you wear a layer of silk or rayon next to a layer of wool—say a rayon sports shirt under a woollen pullover, or a rayon slip under a woollen dress. If you peel the two layers off together, then shake them apart, the electric charge is so strong that you can hear the crackle and, in the dark, see the electric sparks as the electrons jump back from the negatively charged garment to the positively charged one.

ELECTRIC CURRENT

Electrons jumping from one object to another give an electric spark; but if a constant stream of electrons is moving from one atom to the next and to the next and so on, we get an electric current. The electric current which works the electric light in your house flows along a wire which is made of a metal, usually copper. Metals are very much better conductors of electricity than non-metals; electrons can pass from one atom to another far more easily. But something has to start the current off and keep it flowing. There must, in other words, be something to give the stream of electrons a pretty good and continuous push in the right direction. In a torch battery this push—or electric pressure—is provided by the chemical compounds inside the battery. The molecules of these compounds become ionised—they split up into smaller groups of atoms, one kind having extra electrons and therefore having a negative charge, and the other kind, having lost some electrons, with a positive charge. The ions act on the two terminals of the battery. One terminal receives a whole lot of extra electrons from the negative ions. It therefore has a strong negative charge. The other loses a lot of its own electrons to the positive ions. It, therefore, has a positive charge. If the terminals are connected by a piece of copper wire, the extra electrons on the negative terminal push their way into the first atoms of the wire which in their turn push some of their electrons into the next atoms, and so on, so that a stream of electrons flows all along the copper until it arrives at the other terminal, where the missing electrons are replaced by the ones arriving.

There are other ways of making an electric current flow along a wire, but whatever it is that supplies the electric pressure, the current itself always consists of moving electrons.

CONDUCTORS AND NON-CONDUCTORS

An electric current will pass quite easily through most metals; we say that metals are good *conductors* of electricity. A few non-metallic elements and a certain number of chemical compounds will also conduct electricity, though far less easily than metals. Materials such as rubber, glass, and porcelain are *non-conductors*.

Some liquids—sea water, for example, which is a solution of metallic salts in water—will also conduct electricity. This is because the molecules of salt in the water have become ionised, and the positive and negative ions themselves move through the liquid, in opposite directions, and carry the electric charges with them.

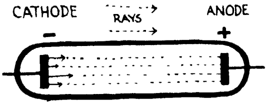
Under ordinary conditions gases, such as air, are such poor conductors of electricity that they are, for all practical purposes, non-conductors. It is, of course, fairly easy to make a single electric spark jump a short distance through air from one charged surface to another. But to make the spark jump a long distance the electric pressure between the two surfaces has to be pretty high. In a thunderstorm, for example, the electric potential between the lower surface of a thundercloud and the ground just before the lightning flash takes place may be as high as a thousand million volts. But the duration of an electric spark, whether it is a lightning flash or the spark between two terminals of a torch when you short-circuit them with a knife blade, is very brief indeed.

DISCHARGE THROUGH GASES

To make a continuous electric current flow through a gas special apparatus has to be used.

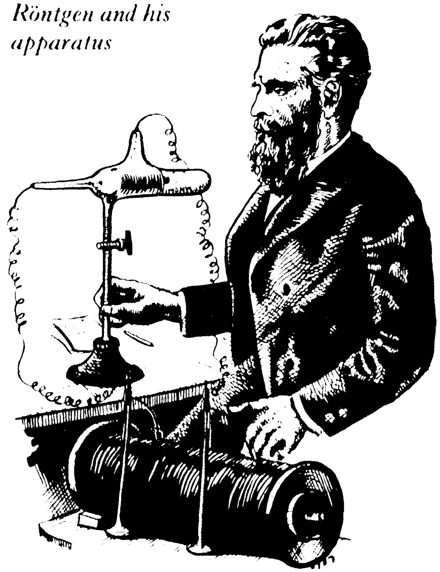
The gas is first enclosed in a glass tube.

Inside the tube are two metal plates, the *anode* and the *cathode*, connected by wires fused through the glass walls of the tube to a source of electricity. If this source is switched on, and the electric pressure between the two plates is high enough, a series of crackling sparks will pass at intervals from one plate to the other. Now suppose the gas inside the tube is gradually sucked out by an air-pump. As the amount of gas inside the tube gets less and less the series of brilliant crackling sparks broadens out into a quiet continuous streamer, and when the amount of gas is reduced to about one thousandth of what was originally there, practically the whole of the tube is filled with a glow that extends from the anode. Tubes of this kind, containing, for example, the gas neon or sodium vapour, are often used as fluorescent lamps for shop signs, advertising, and the street lighting.



As more and more gas is pumped out of the tube the appearance of the discharge goes through a series of beautiful changes until the glow in the gas disappears altogether, although electricity is still passing between the cathode and the anode. It can now be shown that the cathode is giving out a stream of fast moving electrons, known as cathode rays. When these electrons hit a solid object—a plate of metal placed opposite the cathode, or even the glass wall of the tube itself—they make it glow. It is possible, by bringing a strong magnet near the tube, to 'bend' the beam of electrons so that the rays fall on a different part of the tube. If a card painted with a fluorescent chemical, such as barium platino-cyanide, is put in the path of the cathode rays the chemical glows very brightly indeed. The stream of electrons has other interesting properties as well; if there is a small 'window' in the glass tube covered with thin metal foil the cathode rays can be deflected by a magnet until they fall on this window and, if the foil is thin enough, they will go straight through it. Now cathode rays are not like light rays—they are streams of tiny *particles*—electrons. It is true that electrons are very tiny indeed—two thousand of them weigh only as much as the lightest complete atom, the hydrogen atom. But although they are so minute they are, nevertheless, *matter* as distinct from radiant heat or light, which is *energy*. It is therefore rather surprising that they can get through something solid, like metal foil. The explanation is that the atoms of the solid metal, even though they are jammed together pretty tightly so that their outermost shells interlock with each other, are mostly space inside. Only the nucleus in the middle is really solid—the greater part of the atom is empty space threaded through at intervals with the orbits of the various tiny electrons in their different shells. A fast-moving electron fired at the atom from outside might easily shoot straight through this empty space without colliding with the nucleus or disturbing the other electrons already belonging to the atom. So an electron might quite easily be able to pass without collision through a thin sheet of metal. But if the metal were thick, the chances of a collision would be much greater, and if a stream of fast moving electrons impinge on a solid block they are bound to produce a violent effect on the atoms of that solid.

Röntgen and his apparatus



THE DISCOVERY OF X-RAYS

In the year 1895 the great German scientist, Wilhelm Conrad Röntgen, was experimenting with a discharge tube. At this time some of the effects of cathode rays had already been discovered, but their nature was not known, and it was not until two years later that J. J. Thomson showed that they consisted of little particles with a definite charge and a definite mass, and that they were the same whatever material the cathode was made of. But Röntgen knew already that the rays given off by the cathode would make the glass and various other chemicals glow, and he had been experimenting with a card coated with barium platino-cyanide. One evening when all his assistants had gone home Röntgen was working in his darkened laboratory alone. A discharge tube was on his bench—he switched the current on and off to see the glow caused by the cathode rays on the glass. The card coated with barium platino-cyanide was lying on the bench some distance away—Röntgen did not need it at that moment. He now decided to cover the tube completely with black paper. Why? Well, there are various accounts of Röntgen's famous experiment, but none of them really explains just why he had decided to do this. Perhaps he had some kind of hunch that he would discover something interesting. His paper cover was complete—he switched on the electricity again and no light at all could be seen coming from the tube. The room was in total darkness . . . or was it? No—it was *not* completely dark. From the far end of the bench—nowhere near the tube—there came a faint glow. Röntgen went across to investigate. It was the card covered with barium platino-cyanide. It had no business to glow. The cathode rays were cut off most effectively by the black paper, so *they* couldn't be causing the glow. Röntgen switched off the current. At once the glow ceased. He switched it on, and the cardboard shone once more.

Clearly *something* must be coming from the tube which caused the chemical to glow. Some new kind of rays that nobody had before observed. He called them X-rays—'X' for the unknown.

Röntgen discovered that these X-rays had very remarkable properties. They could penetrate thin sheets of metal and quite thick pieces of wood, and could go right through the thickness of a pack of cards. They could also go through flesh, though they were stopped by denser material such as bone. In addition, they would also effect a photographic plate in much the same way as ordinary light, and within a remarkably short time of his original discovery Röntgen had taken the first X-ray photograph of a human hand.

We now know a good deal more about the nature of X-rays than Röntgen did.

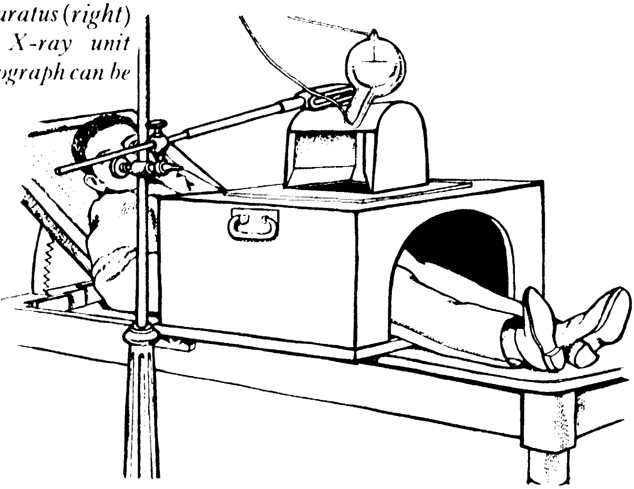
They are of the same nature as light rays, but with very much higher frequency and shorter wave length.

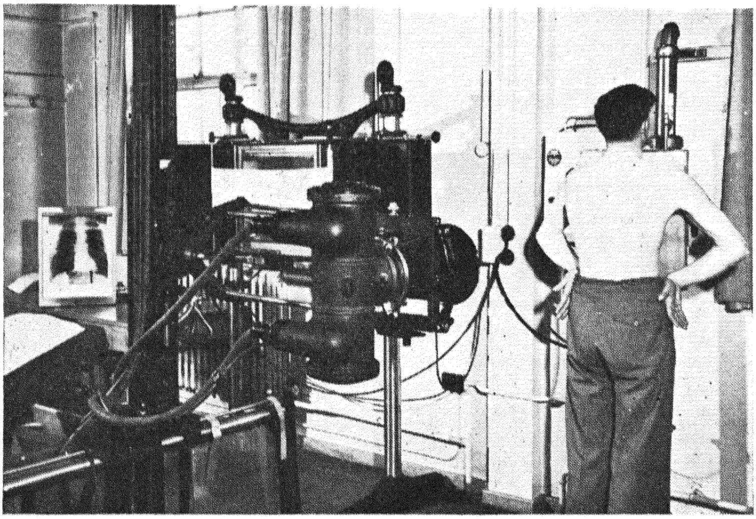
They are produced by the cathode rays in the discharge tube when the fast moving electrons of the cathode rays hit atoms.

When a very fast electron hits the outside shell of an atom it may knock out one of the atom's electrons altogether; this leaves an atom with a positive charge—an ion. This is what happens to some of the atoms of gas in the tube when the beam of electrons hits them. But if the fast electron in the cathode ray hits one of the *inside* electrons of an atom something different might happen. The disturbed electron may jump to a completely different orbit, and the atom is left with an extra bit of stored-up energy. The atom will probably remain in this 'excited' state for only a very short time. The displaced electron may jump back again to its 'home' orbit, or another electron may jump into the unoccupied space. A sort of 'general post' of electrons may take place, but sooner or later all the original orbits of the atom will be occupied once more, and the atom will remain stable again until another fast electron from outside excites it. Every time an electron from inside the atom leaps from one orbit to another a little bit of energy is given out—an X-ray. The frequency of this X-ray depends on the relative positions of the two orbits, and in a large number of atoms all being bombarded by the fast electrons of cathode rays a continuous stream of X-rays of several different wavelengths will be produced.

Those with the shortest wavelength are the most penetrating. They are sometimes called 'hard' X-rays. The waves are small enough to wriggle their way, as it were, through the empty spaces of some atoms—that is why X-rays can penetrate glass and paper and human flesh. But X-rays are, sooner or later, absorbed by matter, and they may cause very pronounced effects. Early X-ray experimenters were unaware of this, and many radiographers lost the use of their fingers because of the harmful effects upon human flesh of a continued series of X-ray bombardments. In a controlled and limited fashion this property of X-rays may be put to good use; X-rays are used

An early form of X-ray apparatus (right) compared with a modern X-ray unit (below). A chest X-ray photograph can be seen to the left of the unit





in hospitals for the treatment of certain diseases, but great care has to be taken to protect not only the operator but also the patient from too severe a dose of the lethal rays.

THE DISCOVERY OF RADIO-ACTIVITY

In 1896—the year after Röntgen discovered X-rays—the French scientist, Henri Becquerel, made an equally important discovery. He had been experimenting with salts of the metal ***uranium.*** Uranium is the heaviest of all the elements found in nature. Becquerel noticed that a uranium salt which was wrapped up in paper, and had been wrapped up for some time, caused a photographic plate to darken as though ordinary light had fallen on it. The uranium was giving out very active rays of some kind, and giving them out quite spontaneously; it was not necessary to do anything to the uranium to make it give off this radiation. And it didn't matter whether the uranium was in the form of a chemical compound or whether it was the pure metal—the rays were given off steadily and at the same rate.

A few years later Marie Curie, one of Becquerel's students, noticed that pitchblende, the ore from which uranium is extracted, was a good deal more radioactive than the pure uranium salt obtained from it. It seemed that it contained another element, even more strongly radioactive than uranium. Marie Curie and her husband, Pierre, succeeded in extracting this new element. They called it radium.

Radium and other natural radioactive elements give rise to three distinct kinds of radiation. They are known as alpha-, beta-, and gamma-rays (α, β, and γ are the first three letters of the Greek alphabet.) The alpha-rays are easily absorbed by thin sheets of solid material, but when they pass through a gas they turn a very high proportion of the gas into ions. The famous British scientist, Lord Rutherford, found that these rays were not radiant energy but a stream of rapidly moving particles. They are in fact, identical with the nuclei of helium atoms —that is, they are solid particles each consisting of two protons and two neutrons, and each having four times the mass of a hydrogen atom. They are shot out from the radio-active elements at a speed of about ten thousand miles a second, and they therefore have great energy. Rutherford later used these alpha-particles for bombarding and splitting up other atoms.

The beta-rays are much more penetrating than alpha-rays, and are less effective in ionising gases through which they pass. They, too, consist of rapidly moving particles—not waves in the same sense as light waves. They are electrons, shot out from the atoms with varying speeds; the fastest may travel nearly as fast as the speed of light. Beta-rays, then, resemble the cathode rays in an X-ray tube, which are also made up of high-speed electrons.

The third kind of radiation, gamma-rays, are not made up of material particles. They are radiant energy, and they travel with the same speed as heat rays, visible light rays, and other forms of radiant energy. Their wave length is even shorter than that of the X-rays discovered by Röntgen and they are, therefore, even more penetrating than X-rays, for the shorter the wavelength the more easily can the rays pass through the spaces inside atoms without being stopped.

From now onwards we shall use the Greek symbols—α, β, and γ. Remember that α-rays and β-rays are both streams of *particles*, whereas γ-rays are radiant *energy*.

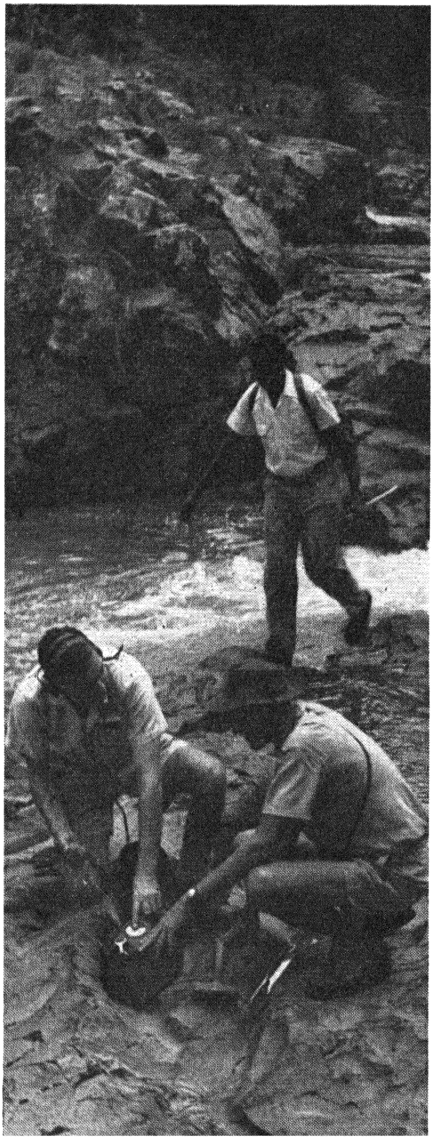
THE URANIUM SERIES

A radio-active element does not give

off all these three kinds of radiation at once. As it decomposes it changes first to one new element, then to another, then to another, and so on. In many of these changes γ-rays are given out in addition to an α- or β-particle; there may be a dozen or more changes involved before the radio-active substance finally settles down for ever as the final element of the series, which is no longer radio-active but quite stable. Radium itself, which is several million times more radio-active than uranium, is, in fact, a half-way stage in the disintegration of uranium. That is why it is always found in uranium ores.

Uranium is the parent of a whole series of radio-active elements. An atom of uranium, with an atomic weight of 238, first loses an α-particle (that is, a helium nucleus) and becomes a new atom with an atomic weight of 234. This now loses a β-particle, which has so little weight that it hardly counts, and becomes an atom of a new element, still with atomic weight 234. (The β-particle, by the way, which you remember is simply a lost electron, is lost not from the shells of revolving electrons, but from the nucleus itself on page 36 we see how this can happen.)

This new element is able to exist only for a very short time; in just over a minute half its atoms will have altered again. As they change, each atom loses another β-particle, so the resulting new element still has an atomic weight of 234. From then onwards a succession of α-particles is lost, and a stage is reached when the atom, now with an atomic weight of 226 has become an atom of radium. This again loses an α-particle, then another, then a β-particle, and so it goes on until



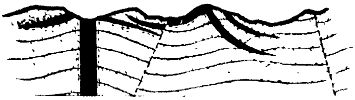
Prospecting in Africa for Uranium, using a Geiger counter an atom is reached which is no longer radio-active. This stable element has an atomic weight of 206, and is an isotope of lead. (Ordinary lead has an atomic weight of 207.)

The successive elements formed in this series have various rates of decay; some may live for only a matter of seconds; others may exist for thousands of years. The total rate at which the original uranium decays to form the final lead is known pretty accurately, and this knowledge is made use of in finding out how old certain fossils may be.

DATING THE ROCKS

The Earth, during its long history, has undergone a number of very slow changes, and at many times new layers of rock have been laid down. Fine particles of mud settle at the bottom of a lake or the sea, burying, perhaps, the bodies of sea creatures or of land creatures that have drowned in the water. Time passes. Perhaps an earth movement heaves up the ocean bed to above the level of the sea. The water evaporates, the mud hardens to rock, enclosing the fossil animal remains. After many centuries the land may sink again, and a new layer of rock may be formed above it by sediment from the water settling and then hardening in the same way; but this time the rock will enclose a different series of fossils. Rock formed in this way is known as *sedimentary* rock.

But another kind of earth movement may also take place. Molten minerals from the hot interior of the earth may force their way up through the layers of sedimentary rock and harden to form pockets of *igneous* rock. This rock, of course, contains no fossils. But it may contain crystals of various uranium compounds. These compounds can be analysed by chemists. They can find out how much of the original uranium is left, and how much lead has been formed. This will tell them how long the uranium has been disintegrating, and therefore how long the pocket of igneous rock must have been there. The sedimentary rock, and therefore the fossils in it, must be as old as this—and probably a good deal older.



Section across part of Derbyshire, with gently folded and faulted sedimentary rocks, and igneous intrusions

HALF-LIVES

When one natural radio-active element changes into another it does not do so, of course, in one big bang. The element contains billions upon billions of separate atoms and, although each of these atoms is capable of changing to the next member of the series they don't all go off at once. Suppose you could isolate a very small lump of a pure radio-active element containing, say, only a thousand atoms. The chances are that within a given time, say 24 hours, a certain proportion of these atoms will have given out an α- or a β-particle and turned into the next kind of atom on the list. Let us suppose that exactly half the atoms change in this way during the 24 hours. Then in the next 24 hours half the remaining atoms will change, in the next 24 hours half the remainder, and so on, until finally there are none left. In this example the period of 24 hours is what we call the *half-life* of the element, and it is the same whatever sample of the element we take. Some members of a radioactive family of elements have a very short half-life. An element called thorium A, for example—which is a member of another series of radioactive elements, the thorium group—has a half-life of less than one fifth of a second. Radiothorium, another element in the same series, has a half-life of nearly two years. And thorium itself, the parent element of this particular family, has a half-life of over ten thousand million years.

In addition to these two families of natural radioactive elements, the uranium family and the thorium family, there is a third series which also occurs in nature. This is the actinium series of elements. In all three cases of these naturally-occurring series the stable end-element is lead, but the three distinct parents—uranium, thorium, and actinium, give rise to three separate isotopes of lead, one with atomic weight 206, another 208, and the third 207.

It is, of course, possible that there may have been other natural series of radioactive elements at one period in the earth's history. The three we know about all have parent elements with a very long half-life. As the earth is known to be at least 2,500,000,000 years old, any parent radio-element with a short half-life would have dwindled so much in that time that the small amount left would probably be undetectable.

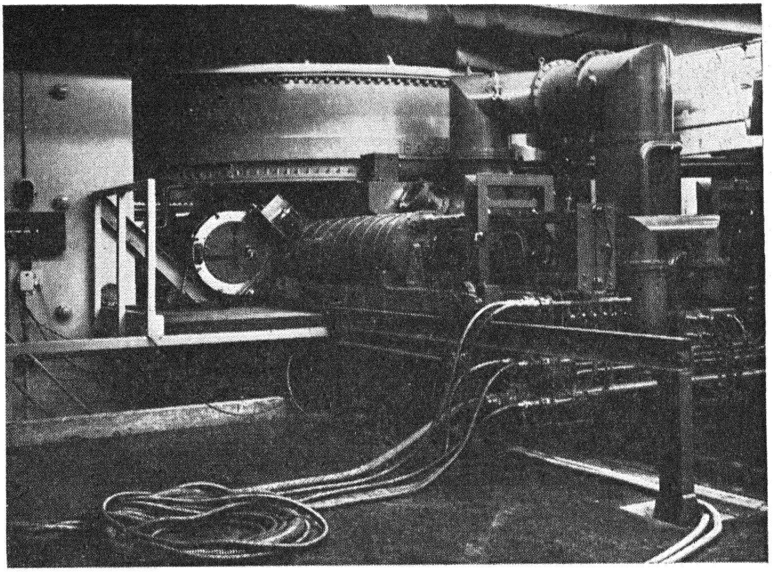
But besides these three natural series scientists have now succeeded in making a similar series of radio-active elements which do not occur in nature at all. The parent of this series is the artificial element Plutonium 241, and it was first made by Seaborg in 1944 by bombarding uranium atoms with α-particles, accelerated to a tremendous speed in an instrument known as a *cyclotron*. This form of plutonium (at least three other isotopes of plutonium have been made, one of which is of great practical importance in the controlled production of nuclear energy) is of particular interest because it is, in fact, *heavier* than the heaviest atom found in nature. The uranium it is made from has an atomic weight of 238. When a very fast α-particle—which is a helium nucleus of atomic weight 4—hits this, it sticks to the nucleus, as it were, but knocks out a neutron, weight 1. $238+4-1=241$, and this is the atomic weight of the new artificial radioactive element.

When Plutonium 241 decays it gives rise to a new series of artificial radioactive elements, thirteen or fourteen in all, but the last one, the stable one, is not an isotope of lead as in the three natural series, but a form of the metal *bismuth*.

RADIOCARBON

In addition to the elements found in nature which are spontaneously radioactive, some elements are made radioactive by natural processes, which man imitates when he bombards atoms in a cyclotron or in an atomic pile.

One of the most interesting of these elements, because it has recently been found very useful as a label for estimating the age of remains of past civilizations, is carbon 14.



A Cyclotron
(*see pp.* 31–32)

Carbon 14 is an isotope of ordinary carbon, whose atomic weight is 12. It is formed by the action of cosmic rays (rays which arrive not from the sun but from outer space) on the nitrogen in the air.

A nitrogen atom also has an atomic weight of 14. Its nucleus consists of 7 neutrons and 7 protons, and it has, of course, 7 electrons revolving round the nucleus to balance the positive charge of protons.

However, when a nitrogen atom is bombarded by cosmic rays changes take place both in the nucleus and in the outer shell of electrons. One of the protons changes into a neutron, which means that the nucleus now contains six protons and eight neutrons. And one of the electrons from the outer shell is lost altogether. The result is an atom with six protons and six electrons—which makes it a carbon atom—but it has eight neutrons instead of six, so it weighs more than an ordinary carbon atom.

The action of cosmic rays in changing a proton to a neutron introduces us to a new kind of atomic particle. So far we have thought of atoms as being made up of protons and neutrons in the middle, and electrons round the outside. Three kinds of brick for building all the atoms in the universe.

But now we learn that a positive proton can turn into a neutral neutron. It can lose its positive charge—and the charge shoots off as a particle of the same size as an electron but with a positive instead of a negative charge. This new kind of particle, the positive electron, is called the *positron*. It was discovered independently by Anderson in America and Blackett in England in the year 1932.

Very little is known about positrons, for usually their life is very short, but they can now be produced artificially by bombarding certain atoms with very high frequency γ-rays.

But let's get back to our atoms of radiocarbon in the air—Carbon 14.

As cosmic rays have been steadily bombarding the Earth's atmosphere since the Earth first had an atmosphere, the amount of carbon 14 in the air is now pretty steady. The gas, carbon dioxide, contains both kinds of carbon—12 and 14. Carbon 14 is unstable—it gradually changes back to nitrogen. But, as far as the air is concerned, the amount of Carbon 14 lost by disintegration is exactly balanced by the amount made by the action of cosmic rays. So the proportion of the two kinds of carbon in the carbon dioxide is always the same.

Now living plants get the carbon they need for body building from the carbon dioxide of the air. This means that a living plant will also contain both kinds of carbon—12 and 14—and they will be always in the same proportions so long as the plant is alive and taking in more carbon from the outside. But once the plant is dead it no longer absorbs carbon dioxide from the air. The carbon 14 inside the plant slowly decays, and no more comes in from the air to take its place. So the longer the plant has been dead, the less the proportion of Carbon 14 it contains.

The rate of decay of Carbon 14 is known, so if, for example, a piece of dead wood is analysed it is possible to tell from the relative amounts of the two kinds of carbon present how long the wood has been dead.

This method of dating organic matter has been very useful for objects such as wooden boats or the charcoal found as ashes on sites of ancient bonfires made by pre-historic man. It is not much good for small valuable objects, for in order to analyse the carbon, the material containing it has to be destroyed. It is also not much good for such organic remains as human bones, which contain very little carbon.

DATING WATER

Another radioactive element formed in the air by the bombardment of cosmic rays is tritium. Tritium (see page 13) is an isotype of hydrogen, with an atomic weight three times that of ordinary hydrogen. The tritium is formed in the upper part of the earth's atmosphere, which contains hydrogen, and a certain amount of it diffuses downwards and is then washed to earth by the rain, which collects in rivers and lakes and trickles downwards to form underground reservoirs. Radioactive tritium has a half-life of about 12½ years.

When deserts are being prospected for underground water supplies a sample of the water from each well can now very easily be tested to find out what proportion of radioactive tritium it contains. If the proportion is high the water must have collected recently, and the well is likely to yield fairly constant supplies of good water. But if little radioactivity is found it is likely that the water was sealed off in an isolated pocket underground a very long time ago, which means that once the water has been exhausted it will not be replenished from other underground supplies.

Lord Rutherford, interviewed in the Cavendish Laboratory, Cambridge

In some parts of the world, such as deserts in Israel, the water from every new source is tested automatically to find out whether it is likely to be a good source that desert settlers can rely on for irrigation purposes season after season.

MAN-MADE ISOTOPES

So far we have met two kinds of radio-active elements found in nature; the first kind, like uranium, are radio-active because their atoms are large and not very stable. They split up spontaneously—they do not need any help from outside. But other radio-elements, like carbon 14, are produced in nature by bombardment from outside—in this case by the action of cosmic rays.

This is the method that man has learned to imitate when he knocks bits off atoms—or adds bits on—to make new elements.

The first thing he needs is a projectile small enough to get inside the atom and hit the nucleus, and fast enough to have sufficient energy to disrupt the nucleus if and when it gets there.

There are various atomic particles small enough to get inside atoms, between the rings of whirling electrons. Helium nuclei are one possibility. On their own they do not move fast enough, but as α-particles shot out of naturally occurring radioactive elements they move with enormous speed, and there are other ways in which they can be speeded up.

The first experiments on changing atoms artificially were carried out in 1919 by Lord Rutherford at Cambridge, in the famous Cavendish Laboratory.

Rutherford reasoned that the α-particles shot out by a natural radioactive substance would be heavy enough and fast enough to change the nucleus of a fairly light element. The nucleus of an element has a positive charge—the sum of all the positive charges of its protons. So the larger the nucleus the greater its positive charge. An α-particle—which is, remember, a helium nucleus—also has a positive charge. Positive charges repel each other—so the α-particle must travel at enormous speed in order to have enough energy to overcome the repulsion of the other nucleus. The heavier the nucleus, the more repulsion the α-particle will have to overcome. Rutherford decided to try the effect of α-particles on nitrogen, which is not too heavy. The difficulty was to detect when the atoms had been changed.

A single α-particle causes a minute splash of light to appear for a short time on a phosphorescent screen, and this speck of light can be seen quite easily through a low-powered microscope. A beam of α-particles can be made to point in a certain direction, and their separate tracks can be mapped out by the splashes of light they cause.

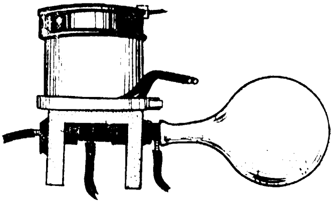
Other kinds of particle can also cause flashes of light on the screen, and Rutherford found that when he passed the beam of an α-particle through nitrogen he saw flashes which showed that they must had been made by particles a good deal lighter than α-particles. He proved, by measuring their deflection with a magnet, that these particles were *protons*. They could only have come from the nitrogen. If an α-particle actually managed to hit a nitrogen nucleus it chipped off a proton which flew off with tremendous energy. The α-particle was itself captured by the nitrogen nucleus, and changed it into a new and heavier element—in fact, an isotope of oxygen.

In the year 1934 the first artificial radioactive element was made, by the French scientist, Joliot, and his wife Irene Curie, daughter of Marie Curie. They bombarded aluminium with α-particles from a natural source, and found that the aluminium gave out not α- nor β- nor γ-rays, but *positrons*—positively charged electrons. Moreover, it continued to give out these particles even after the bombardment had stopped—in other words, it behaved like a natural radioactive element, with its radiations getting weaker as time went on.

THE WILSON CLOUD CHAMBER

The apparatus which the Curie-Joliots used to detect their positrons was not a phosphorescent screen, which is very trying to the eyes of an observer, but an even more useful piece of apparatus known as a cloud-chamber; it was invented by C. T. R. Wilson. It depends on two facts: first, that when an α-particle flies through a gas it grazes the outsides of numerous atoms on the way (apart from the few that it hits fairly and squarely in the middle) and so knocks off a whole trail of electrons. The atoms of gas minus their electrons have, of course, a positive charge; they have become ionised.

The second fact is that if the gas also contains a certain amount of water vapour, and if this is suddenly cooled, it will condense as droplets of water. But each drop needs something to start it off, something for the water to condense on. A speck of dust will do; so will an ion of gas or even a single electron. When clouds are formed in nature this is how they start, and Wilson was simply making a small artificial cloud in his laboratory.

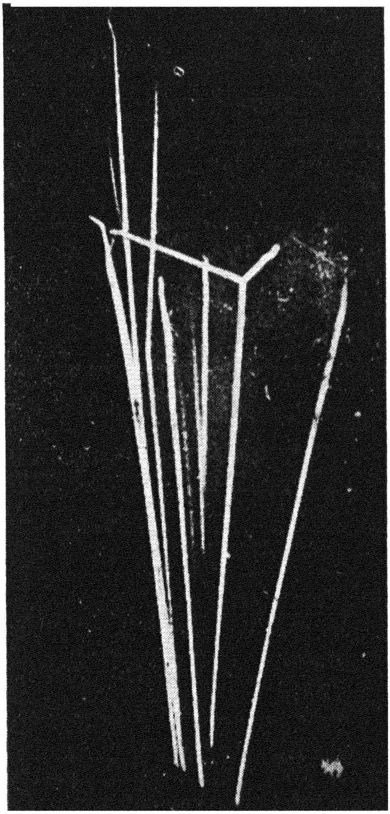


An early form of Wilson's cloud chamber. The cylinder, glass-topped and containing a piston, was filled with moist air or gas. A vacuum was created in the spherical flask. A pull on a plug linked the two, the piston was sucked downward and the air in the chamber cooled by the sudden expansion.

The method is simple. Moist air is enclosed in a glass container and suddenly cooled. At the same time α-particles are shot through the gas, each leaving a trail of electrons and charged atoms or ions, behind it. The cooled water vapour immediately condenses on this row of ions and electrons, and the trail can actually be seen as a white line in the cloud-chamber, like a miniature vapour-trail of an aircraft.

In modern cloud chambers automatic cameras are used to photograph the vapour trails; each trail corresponds to the path of one single particle.

The track of an α-particle will normally be a straight line. But if it should collide with something solid, like the nucleus of an atom, it will either bounce off in a different direction or be absorbed altogether, and a lot can be learned about the structure of atoms from the way they behave on collision. Sometimes other particles may shoot out from the nuclei that are hit by the α-particles. These, too, leave vapour trails in the cloud chamber. It is possible to bend the paths of the particles by bringing strong magnets near the cloud chamber, and by measuring the



Cloud-chamber photograph with vapour-trail showing collision of otherwise invisible particles amounts that the vapour paths are curved, the charges of the particles and their energies can be calculated.

MATTER FROM ENERGY

The existence of positrons (electrons with positive instead of negative charges) can be shown in the cloud chamber. If very high frequency γ-rays are passed through the cloud chamber, occasionally a small parcel of energy from the γ-rays may be absorbed by an atom, which then simultaneously gives off an electron and a positron. The electron and the positron do not, in this case, come from the nucleus, neither do they belong to the other part of the atom in its normal state. They are actually created at the moment of impact by the energy from the γ-radiation. In other words, *energy has been turned into matter*. The tracks of electron and positron can be seen bending away from the atom in opposite directions when the cloud chamber is placed in a magnetic field.

It has also been possible to observe what happens when an electron and a positron meet each other; both are destroyed—but there is a sudden emission of radiation. In this case *matter has been changed into energy*.

So the old idea that matter was matter, and energy was energy, and that the two were quite separate and distinct has been proved wrong. Still, for all practical purposes we can continue to think of them as different in their nature.

(In addition to positive electrons, negative protons have also been detected. There may also be neutrons of a nature completely different from ordinary neutrons. If these anti-neutrons combined with negative protons and positive electrons they might produce a new kind of matter—anti-matter—which would be the exact opposite of matter as we know it. If some anti-matter came in contact with ordinary matter, the two would exactly cancel out and both would disappear completely with the formation of an intense amount of energy. This is a theory that has been put forward to suggest why some large meteors known to have fallen on the Earth have left no trace except a crater. It is only a very tentative theory—no-one has yet any evidence that anti-matter really exists.)

THE GEIGER COUNTER

One of the most useful instruments for detecting radioactivity was invented by Rutherford and Geiger, and improved by Geiger and Müller in 1928. It is known as the Geiger counter. The principle on which it works is very simple. A small amount of gas at low pressure is enclosed in a tube which also contains two metal electrodes. When an α-particle or a β-particle or γ-radiation enters the chamber it causes momentary ionization in the gas, and the current which then passes between the electrodes can be registered as a 'click' or as the kick of a needle on a dial. Since this sort of apparatus is portable it is of great value, for example, in prospecting for uranium ore.

LINEAR ACCELERATORS

The first way that man succeeded in changing atoms was to use the projectiles provided by nature—the fast moving α-particles shot out by a radio-active element. The difficulty about this method is that no natural radio-active element gives

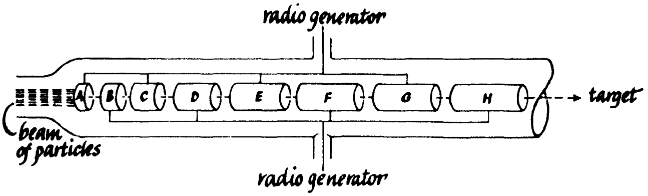


Diagram of a linear accelerator

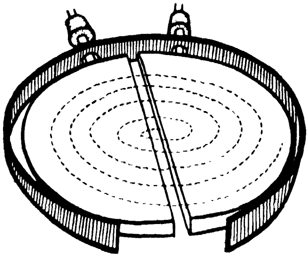
off a concentrated enough stream of these particles to be of much practical use.

It is easy enough to produce small particles without starting from a radioactive source—the difficulty is to give them the necessary speed, and therefore energy, for shooting into atoms. But there are various ways in which this can now be done. In one kind of accelerator, positively charged particles—usually protons—are passed through a series of hollow cylinders arranged in a straight line. The cylinders are connected to the terminals of an alternating generator in such a way that alternate cylinders are positively and negatively charged.

The positive particle first passes down a negative cylinder, then it comes to a gap. At this point the charges on the cylinders are reversed, and the particle leaps away from cylinder A, which is now positive and repels it, across the gap to cylinder B, which is now negative and attracts it. As it leaps, its speed of movement gets greater. At this increased speed it sails down cylinder B, which is slightly longer than cylinder A, and by the time it arrives at the next gap the cycle has changed again. It leaps across to cylinder C, now negative, again increasing its speed, and this happens again and again all along the line. The cylinders alternate their charges at a regular rate, so as the particle gets faster and faster along the line, the cylinders have to be longer and longer in order that the particle shall not arrive at the next gap too soon. This means, of course, that the *linear accelerator* is a cumbersome piece of apparatus. But the stream of particles shooting out at the far end have much more energy than those going in, and are correspondingly more effective as bullets for shooting into atoms.

THE CYCLOTRON

Another kind of particle accelerator, invented by the American scientist Lawrence in 1930, is the *cyclotron.* The particles may be protons or deuterons (a deuteron is the nucleus of a deuterium atom—it consists of one proton and one neutron) or helium nuclei (artificial α-particles). They are again accelerated by an alternating potential, which this time is applied across the two halves of a flat circular metal box, like a large shoe-polish tin sawn down across the middle,



Principle of cyclotron

with the two halves slightly separated. This box is enclosed in a vacuum.

The positive particles are started off on their journey near the centre of the box. If left by themselves they would, of course, travel in a straight line, but the whole apparatus is placed in a strong magnetic field so that the path of each particle is bent round into a circle. Each time a particle comes to the gap between the halves of the box the charge on the two halves is reversed, and the particle is pulled across to the other side, gaining speed as it leaps. The faster it travels the less effect the magnetic field has on it, so the curved path becomes less curved—in other words the circle becomes an ever-widening spiral. The particle gains more and more energy every time it jumps the gap, and the increased speed is such that, no matter how far it has to travel in one complete semicircle, it always arrives at the gap just as the potential changes. When they reach the outside of the box the particles are drawn through a thin window by a charged electrode, and then can be directed on to the material that the scientist wants to study. The particles now have enormous energy.

Another kind of particle accelerator is known as a *betatron*. This, as its name implies, is used for accelerating electrons, which, when they are travelling very fast, are identical with the β-particles produced from natural sources. High energy electrons are of particular value in medical research as they can be used for producing high energy X-rays.

SPLITTING THE ATOM

So far we have seen how natural radioactive elements can gradually lose successive bits of their nuclei and so turn into new elements whose atomic weights are rather less. And we have seen how man, by directing a stream of high energy particles at certain other atoms, has managed to chip pieces off their nuclei or add small bits on.

When a proton or a neutron or a small group of protons and neutrons, like an α-particle or helium nucleus, is knocked out of a large atom, a good deal of energy is released, most of it as the energy which makes the particle move but some of it as very high-frequency radiation, such as X-rays or γ-rays.

Although a very large amount of energy is released when small bits are chipped off a nucleus, there must be a great deal more energy stored up inside the larger part of the nucleus, which remains as a solid lump of protons and neutrons bound tightly together.

In 1919, when Rutherford was carrying out his famous experiments which led to our present knowledge of the structure of the atom, only electrons and protons had been definitely identified. Rutherford foretold the discovery of neutrons in 1920, for he had deduced that these neutral particles must exist in the nucleus in addition to protons. But he failed to find them himself.

In 1932 Chadwick found that when the metal beryllium was bombarded with α-particles it gave out, not protons as had been expected, but particles of the same weight as protons but with no charge. These were, in fact, the neutrons, whose existence had been foretold by Rutherford twelve years earlier. One of the reasons why neutrons had not been discovered before was that as they are neutral they

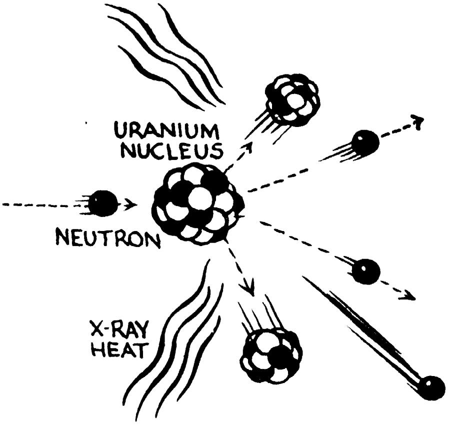


Diagram showing rupture of uranium by a neutron

do not cause ionisation of gases, and cannot be detected in a cloud-chamber in the same way as protons or other positive particles.

Neutrons proved to be a very much better kind of projectile for hitting the nuclei of atoms than protons or deuterons or α-particles, all of which have a positive charge. All nuclei also have a positive charge. And, as there is a strong repulsion between any two positive charges, a positive particle fired into a positive nucleus must use up a great deal of its energy of motion merely in overcoming this repulsion, so less is available for dislodging bits of the nucleus. A neutron does not suffer from this disadvantage. As it has no charge at all it is neither attracted nor repelled by the electrical force of a nucleus, and so it lands on the nucleus with all its energy of motion still available.

In 1938 Hahn and Strassman were experimenting with neutrons, using them to bombard atoms of the heaviest element that exists in nature, uranium. Up till that time many scientists had tried bombarding uranium atoms with various kinds of particle and the result had usually been that small bits of the nucleus were dislodged, leaving atoms with a slightly lower atomic weight.

However, Hahn and Strassman found that the products of their experiments—bombarding uranium nuclei with neutrons—were not elements with *slightly* lower atomic weights than uranium, but two quite unexpected elements, barium and krypton, one of which has an atomic weight rather more than half that of uranium, and the other rather less than half. Apparently what had happened was that the uranium nucleus, instead of having small bits chipped off it as had been expected, had been split by the neutron into two fragments of much the same size. This kind of splitting of the atom is known as *nuclear fission.*

It is now known that various kinds of fission of a uranium atom can take place. The two large fragments formed from one uranium atom of atomic weight 235 may have atomic weights ranging from 72 to 158. One such possible pair of atoms is molybdenum 95, and lanthanum 139. If we write the weights under the particles we get:

uranium +	one neutron =	molybdenum +	lanthanum
235	1	95	139

These, of course, do not add up correctly. The left hand side comes to 236, the right hand side to 234. What happens to the extra weight? The answer is that whereas one neutron shot into the nucleus, two neutrons shot out.

uranium +	one neutron =	molybdenum +	lanthanum +	2 neutrons
235	1	95	139	2

We can now see that this reaction is extremely important in one respect—it gives us a way of doubling the number of neutrons available for doing such work as splitting more atoms.

But there is another interesting result as well.

The answers given for these atomic weights are, in fact, not quite exact—they are the nearest whole numbers.

If more exact weights are compared a surprising thing is found. Here are the actual weights:—

uranium + one neutron = molybdenum + lanthanum + 2 neutrons
235.124 + 1.009 = 94.945 + 138.955 + 2.018
Total 236.133 Total 235.918

This gives us a mass of 0.215—nearly a quarter of the weight of a proton—unaccounted for. What has happened to it? *It has changed into energy.* The two nuclear particles, molybdenum and lanthanum, both have positive charges, and the moment they are formed they repel each other violently, shooting apart with tremendous energy. This energy of motion is changed into heat as soon as the two particles are slowed down by hitting other atoms, and the tremendous amount of heat formed by a vast number of such collisions is responsible for the great disruptive force of the explosion within an atomic bomb.

WHAT HOLDS THE NUCLEUS TOGETHER

This is the point at which we should say something about one of the most difficult things to understand in nuclear science.

If positive charges repel each other, and if the nucleus of an atom contains—in the case of uranium—no less than 92 protons, each with a positive charge, why doesn't the whole nucleus just blow up spontaneously? What possible force can hold the protons so close together, against their nature, as it were? One way of imagining such a force is to think of the nucleus with its tightly packed protons and neutrons as being rather like a single drop of water. The molecules in a drop of water are not firmly bound to each other, yet the drop remains as a drop because the molecules at the surface form a kind of skin by the action of the force known as surface tension.

When protons and neutrons are in very close contact with each other it seems that new kinds of force comes into action, short-range forces which overcome the repulsion that the positive particles have for each other. These act in a way that can be compared to the surface tension of water. This, of course, doesn't explain what a short-range force *is*.

Scientists have suggested a number of theories about all this.

We know that, under certain conditions, neutrons and protons can change into each other. A proton can lose a positron and become a neutron. Or it can gain an electron and become a neutron. Or a neutron can gain a positron or lose an electron and become a proton. These changes, of course, involve changes of energy into mass and vice versa, for both electrons and positrons are matter, though their masses are small compared with those of protons and neutrons. But it has already been proved in cloud chamber experiments, that matter and energy *can* be interchangeable. And if the protons and neutrons in a nucleus are constantly swapping electrons or positrons or small parcels of energy, this may explain why the nucleus as a whole sticks together.

According to another theory, the exchange particles which oscillate between the protons and neutrons are not electrons or positrons, but a different kind of particle a good deal heavier than these, though still much lighter than protons. These particles are known as *mesons*. The existence of mesons in the upper air was demonstrated in 1947 by Professor Powell of Bristol, who sent balloons into the upper atmosphere to a height of 100,000 feet. Mesons are produced by the action of cosmic rays, and there are a number of different kinds, some positive, some negative and some neutral. They arise in the air by the conversion of energy into matter and they have also been produced artificially in other ways—for example, by bombarding graphite with fast helium nuclei produced in one of the fastest type of particle accelerating machines. So far not a lot is known about mesons, except that their life is always very short, but they may play some part also in nuclear structure.

At any rate, inside the nucleus there seems to be constant exchange going on between the particles, and these 'exchange forces' bind the particles together. It seems probable, too, that the protons and neutrons are arranged in a definite pattern in layers, rather like the shells of electrons in the outer regions of the atom. But however it sticks together, the nucleus in most cases is a pretty stable affair —that is, until something comes along to shoot it up.

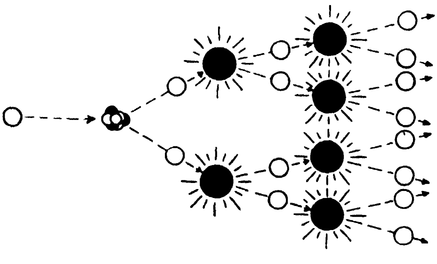
CHAIN REACTIONS

By far the most effective bullets, as we have seen, for shooting atoms are neutrons, and they have a particularly violent effect on uranium atoms.

Uranium exists in nature in three isotopes, one with an atomic weight of 234, one of 235, and the most common of 238.

Uranium 234 is very scarce, and we need not bother about it here. But Uranium 235, which makes up rather less than one part in a hundred of all the uranium, and Uranium 238, the most common kind, are both of great importance.

Uranium 235 was the material used in the atomic bomb that was dropped on Hiroshima at the end of the second world war. If a piece of pure Uranium 235 is hit by a neutron—and there always are a few neutrons about as the result of cosmic ray action—one of its atoms undergoes fission and two or even three more neutrons are released in the process. If the piece of uranium is a small one the neutrons probably shoot out into the air and are lost before they do any damage. But if the piece of uranium is big enough each of the neutrons will disrupt another atom, releasing two or three more neutrons, and each of these will smash a further atom, and so it goes on, each small explosion being followed by not just one, but two or three others. In a fraction of a second the chain reaction, as it is called, will have spread right through the piece of uranium, and the whole thing will blow up with tremendous force, releasing a colossal amount of heat. But this only happens if the piece of uranium is big enough for the neutrons to make their impact before they can escape altogether.



Neutrons causing chain-reaction

If two small 'safe' pieces of Uranium 235 are brought together the resulting lump may be big enough to explode, and this is, in fact, the principle used in the uranium bomb.

Now let us see what happens to Uranium 238 when this is bombarded by neutrons.

In the first place the very fastest neutrons, which are able to disrupt Uranium 235, have little effect on the heavier atoms. But if the neutrons are slowed down a little they are more easily captured by Uranium 238 than Uranium 235. (Very slow neutrons can still produce fission in 235 though they have no effect on 238.)

When an atom of Uranium 238 is hit by a neutron moving at a fairly fast speed the atom hangs on to it. It does not split up, but it turns into an atom of another isotope, Uranium 239; this then gives out a β-particle and becomes a new element, Neptunium 239, which in its turn gives out another β-particle and becomes yet another element Plutonium 239. (The β-particles both come from the nucleus; the loss in each case involves a neutron changing into a proton.)

Plutonium 239 is a fairly stable element; if left on its own it undergoes radioactive decay, but only very slowly. As it is a different element from its parent uranium, it can be separated from a mixture with uranium by the ordinary chemical processes used for separating elements. (Separating two isotopes of the *same* element from a mixture is much more difficult, as both behave alike towards ordinary chemical reagents.)

But although pure plutonium is relatively stable, if it is bombarded by neutrons it undergoes fission in very much the same way as Uranium 235, each separate nuclear fission resulting in three new neutrons, and so giving rise to a highly explosive chain reaction. Plutonium has been used in atomic bombs.

ATOMIC PILES

In order to release nuclear energy from uranium in manageable amounts, that is, enough to be useful, but not enough to explode the whole mass of uranium at once, an arrangement called an atomic pile is used.

The first atomic pile was built by Professor Fermi and first operated in Chicago on the 2nd of December 1942.

The uranium used was the naturally-occurring mixture of both isotopes, 238 and 235. It was in the form of short rods, an inch across and only a few inches long. These rods were inserted into bricks made of graphite, a very pure form of carbon, and the bricks were so arranged that the rods were about 8 inches apart. The point of the carbon is that it does not change when neutrons strike it, though it does slow them down considerably. The carbon is known as a moderator—it moderates the speed of the neutrons.

The reaction starts inside a uranium rod with the production of fast neutrons. The object of Fermi's pile was to manufacture plutonium, so the speed of the neutrons had to be such that just enough would cause the lighter isotope, Uranium 235, to split up and produce a steady supply of neutrons, but that most of these should then be used to turn Uranium 238 into plutonium. If a neutron hit a Uranium 235 nucleus three fast neutrons would be produced. These would probably escape from the small rod into the moderator and perhaps some of them would be lost from the pile altogether. But others would be considerably slowed down. They might then wander back into a uranium rod, and they would now be at the right speed to react either with Uranium 235 or Uranium 238. Those that hit 238 would convert it into plutonium. Those that hit 235 would set free three more nuclei which would follow the same history.

Everything in this kind of atomic pile depends on the exact control of the neutrons. If too many are produced they might trigger off the explosive kind of chain reaction of Uranium 235 that takes place in the atomic bomb. If too few are produced the whole process slows down and may stop altogether. Exact control of the neutrons is affected by rods of cadmium which can be pushed into or pulled out of the pile. Cadmium, unlike graphite, absorbs neutrons very readily, so if the rate of neutron production seems to be becoming too rapid the control rods can be pushed into the pile to absorb some of the neutrons. As an extreme safety measure some extra rods of cadmium are suspended above holes in the pile by means of powerful electro-magnets. The touch of a switch can release these, and they instantly drop into the graphite, absorbing all the neutrons and shutting the pile down altogether.

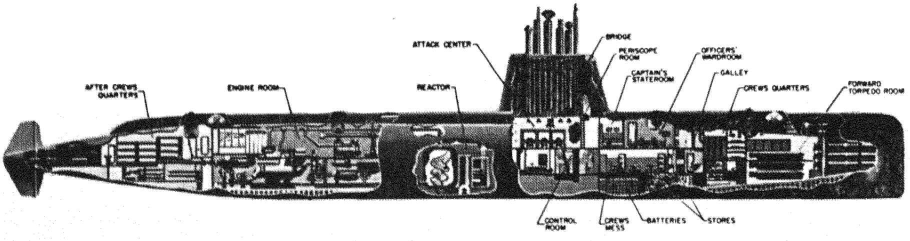
Fermi was not interested in the production of heat in the pile. In fact, this was deliberately allowed to go to waste. But in later piles the heat produced has been made to heat water or a gas or sometimes a liquid metal, and so much heat is given off that it can be used to work turbines similar to those in a power station, with the consequent production of electricity.

POWER REACTORS

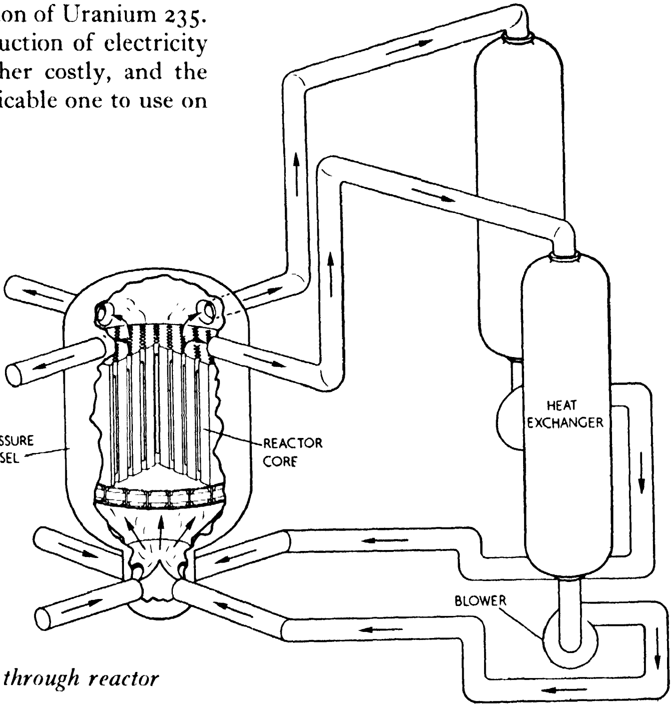
The first practical reactor to be used for the production of power was the engine of the American submarine *Nautilus*, named after the 'Nautilus' of Jules Verne's story, *Twenty Thousand Leagues under the Sea*.

In this reactor the moderator used is not graphite but water, and this is prevented from boiling by a very thick steel pressure container. The water circulates round the uranium rods and then goes to a heat exchanger where steam is raised to a high temperature and used to drive the turbine. The disadvantage of this type of reactor is that water not only slows down neutrons but also absorbs them, unlike graphite which merely slows them down. For this reason the uranium has to be enriched with some extra Uranium 235 to increase the supply of neutrons, and the production of this is a very costly business. All the same, small reactors of this kind have obvious advantages. The first powered surface craft was launched in December 1957. It was a Russian ship, the *Lenin*, and was designed to stay at sea a whole year without re-fuelling. It seems likely that the use of nuclear reactors at sea is something that will develop, but reactor-powered land vehicles such as trains, and reactor-powered aircraft are less practicable; there is more danger of accidents in crowded areas. The production of atomic energy on land is far safer if carried out in atomic power stations.

A small-scale land-based power station, of smaller power rating than that of the *Nautilus*, was built in Russia and operated in 1954. It combines some features of Fermi's reactor with others of the water-cooled *Nautilus* reactor. The moderator is graphite, but water is used for the heat-exchanger. As in the case of the reactor in the *Nautilus*, the uranium fuel has to be



The U.S. atomic-powered submarine 'Nautilus', with reactor amidships. The 'Nautilus' made history in 1958 by making the first North Polar crossing beneath the ice-cap enriched by the addition of Uranium 235. This makes the production of electricity from this reactor rather costly, and the method is not a practicable one to use on a large scale.

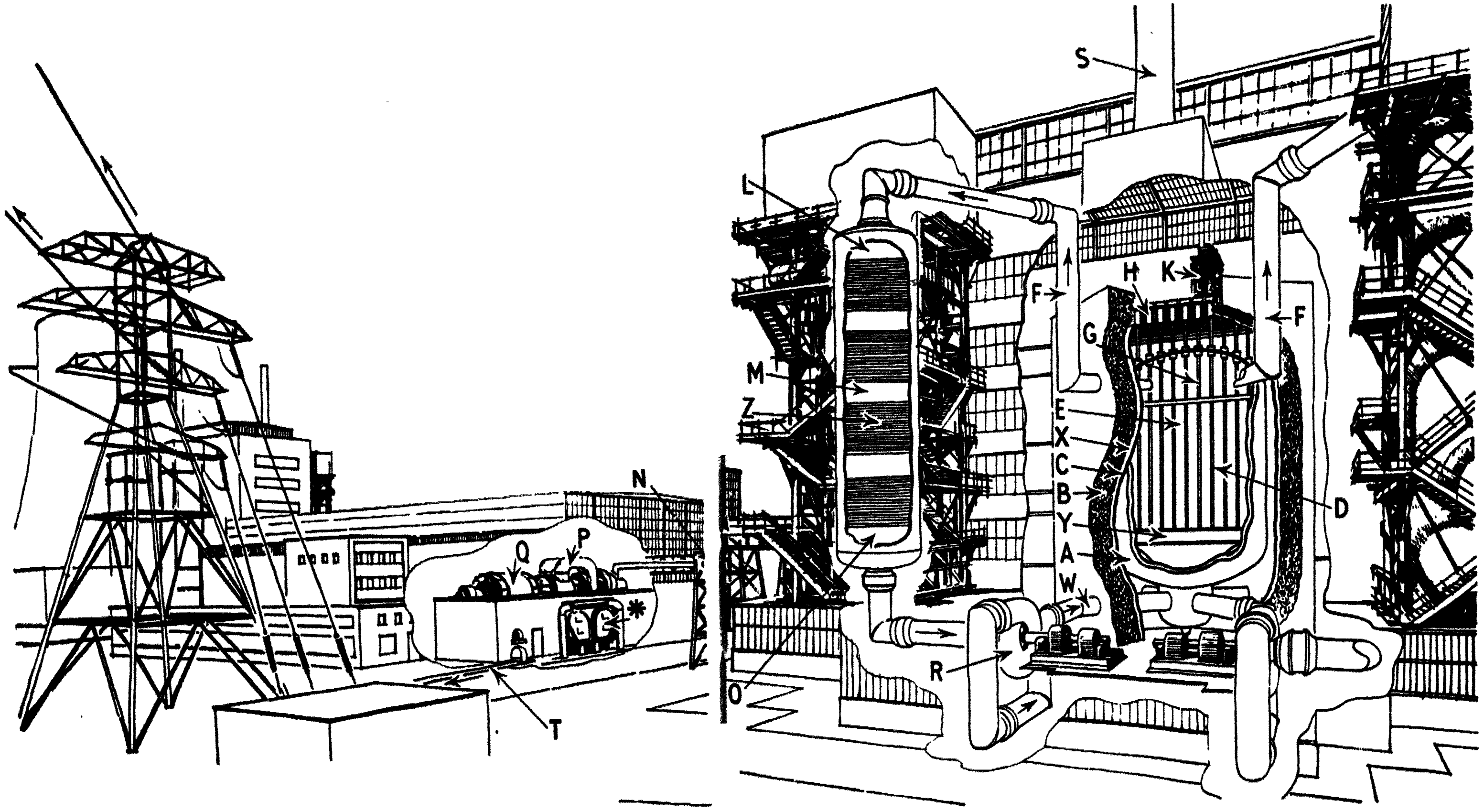


Calder Hall: gas flow through reactor

BRITISH REACTORS

The first nuclear power station in the world to generate electricity on an industrial scale was opened in Britain at Calder Hall, in Cumberland, on 17th October 1956—'a date', as one newspaper put it, 'that will go into the textbooks as the start of a new era'. There had already been several experimental piles in use in Britain—for research purposes in the Atomic Energy Authority's Research Establishment at Harwell, and at Windscale for the production of plutonium.

The Windscale reactors, designed in 1947, had introduced a new principle. They were cooled by an air-plant instead of by water. At first it had been thought that the power needed to pump gas under high pressure through the reactor and the high pressure casing necessary to contain the gas would be too costly and difficult to design. Then engineers working for the Industrial Group of the Atomic Energy Authority suggested a more efficient way of extracting the heat from the uranium rods; the rods were already encased in aluminium tubes, and now each tube was extended along its length with a series of fins. Aluminium is a good conductor of heat, and the heat generated in the rods quickly spread out through the fins, and



A diagrammatic view of Calder Hall

A. Pressure vessel
B. Biological shield (concrete)
C. Heat shield (steel)
D. Uranium fuel elements
E. Graphite moderator bricks
F. Hot gas outlet
G. Control rods
H. Charging tubes
K. Charge/discharge machine
L. Hot gas inlet
M. Heat exchanger
N. Steam pipe to turbine
O. Cool gas outlet
P. Steam turbine
Q. Alternator
R. Regulating gas fans
S. Cooling air chimney
T. Cable duct to transformers
X. Cap for cooling air
Y. Diagrid
Z. Water tubes
** Condenser*

this gave a very large area for the gas to cool them. It was then found unnecessary to pass the gas through the reactor at the very great pressure which at one time had been thought essential. The Windscale reactors were mainly concerned with plutonium production.

The reactor in use at Calder Hall makes use of the same principle of finned containers, but as the main object here is the production of power, as much as possible of the heat produced had to be extracted quickly. To generate electricity efficiently high-pressure steam is needed, and high pressures mean high temperatures. So the gas—in this case not air but carbon dioxide—is blown at high pressure through the enormous container which encloses the complete core. This container is 37 feet in diameter, 60 feet high, and is made of steel with a wall two inches thick. It is surrounded by an octagonal shield of reinforced concrete.

The core itself is made of graphite, 1,000 tons of it. The graphite has to be very pure indeed—even a minute amount of impurity would absorb enough neutrons to slow down the whole process and bring it to a standstill. The uranium rods weigh 100 tons. They are suspended, each in its finned container made of magnesium-aluminium alloy, in channels in the graphite, and the carbon dioxide is blown up the channels in the core at a very high pressure. Control rods can be lowered into the pile from above, and at intervals the enriched uranium rods now containing the new element, plutonium, can be removed. The hot gas is led away from the top of the reactor to enormous towers called heat exchangers. Here it flows between banks of boiler-tubes where water is changed to steam at a high temperature. The steam is led to steam turbines which work the ordinary type of generator for producing electricity.

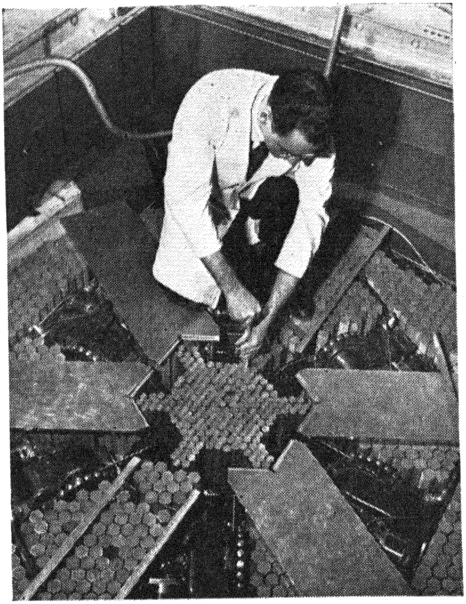
The first town ever to be served entirely by electricity from atoms was Workington, a town near Calder Hall. But the power produced in Calder Hall is not just used locally; it is fed into the national grid.

Calder Hall is the first of Britain's nuclear power stations but a number of others, using an improved type of reactor, are being built, and before very long the greater part of Britain's electricity may be produced in this way, with a consequent saving of coal which is far more valuable in the steel industry and as a raw material for producing drugs, dyes, plastics, and other chemicals, than as a fuel.

BREEDER REACTORS

One of the disadvantages of the uranium rod type of reactor is that the fission products formed when the uranium splits up are themselves capable of absorbing neutrons, and so the longer the rods remain in the pile and the more concentrated the fission products, the more neutrons will be wasted by being absorbed where they are not wanted. So from time to time the rods must be removed, the plutonium and the fission products extracted, the uranium purified, and the rods put back again.

In another possible type of reactor the uranium may be not in the form of a rod of the solid metal, but as a salt dissolved in water. It is contained in a spherical vessel, round which is a second vessel filled with a thorium salt solution. The thorium absorbs any neutrons escaping from the uranium. Both liquids can be pumped through heat exchangers, and they can also be treated by a continuous chemical reaction process to remove the fission products.



Arrangement of rods in a small reactor core, Zeus, at Harwell

In another possible type of reactor the uranium and the thorium are both dissolved in another metal, liquid bismuth; the fission products and the heat can both be removed fairly easily, and the thorium in the outer breeder blanket which absorbs the neutrons undergoes a variety of changes, becoming eventually a new isotope of uranium, Uranium 233. This, like the natural isotopes of uranium, is fissile and so forms a valuable atomic fuel. The interesting thing is that since each uranium atom that splits up gives out more than one neutron, and since each neutron can produce one new uranium atom, a reactor of this kind actually produces more fuel than it consumes. A reactor of this type is called a *breeder reactor*, and one has been built at Dounreay in the north of Scotland. This may also use Uranium 238 in the breeder blanket, and so produce plutonium.

ATOMIC FUSION

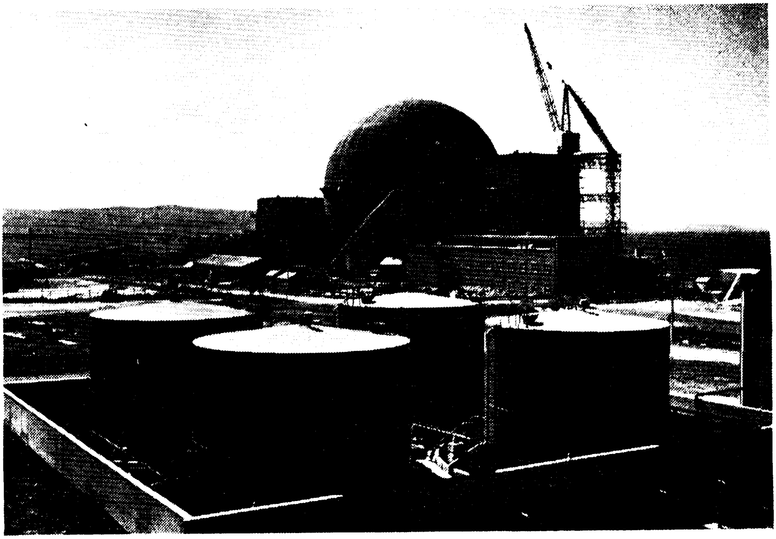
So far we have been thinking mostly of the energy that is released when very large atoms are split up. This is a method that can cause spontaneous explosions on a very large scale, or it can be brought under control and regulated to give a ready flow of energy.

But most of the energy we use on the earth comes from another kind of nuclear reactor, from the joining together of very small atoms, hydrogen atoms, to make larger ones. The natural power station already making use of this principle is, of course, the Sun, and it has been pouring out energy from the fusion of nuclei for billions of years, and is likely to continue doing so for billions more.

Until recently, the main application of the principle of nuclear fusion on the Earth has been a destructive one the hydrogen bomb. The first hydrogen bomb was exploded in the Pacific in 1951. But now it has been found possible to produce energy from the fusion of hydrogen in a controlled reactor.

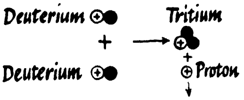
A temperature of several millions of degrees centigrade is necessary to make the hydrogen fuse. In the sun this temperature already exists as the result of past reactions. In the hydrogen bomb it is supplied by a small uranium atomic bomb which then sets off the more powerful one. In the hydrogen reactor a new method is used.

Dounreay

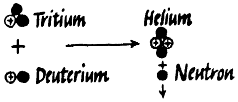


The kind of hydrogen used is deuterium, or heavy hydrogen. This already exists in nature; about one part in 6,000 of the hydrogen in water is deuterium. The deuterium nucleus (page 12), contains one proton and one neutron.

When two very high-speed deuterium nuclei collide they react to form a tritium nucleus, which has one proton and two neutrons, and an odd proton which is the same thing as a nucleus of ordinary hydrogen.



The tritium nucleus may then collide with another deuterium nucleus, and this time a helium nucleus is formed and a neutron shoots off.



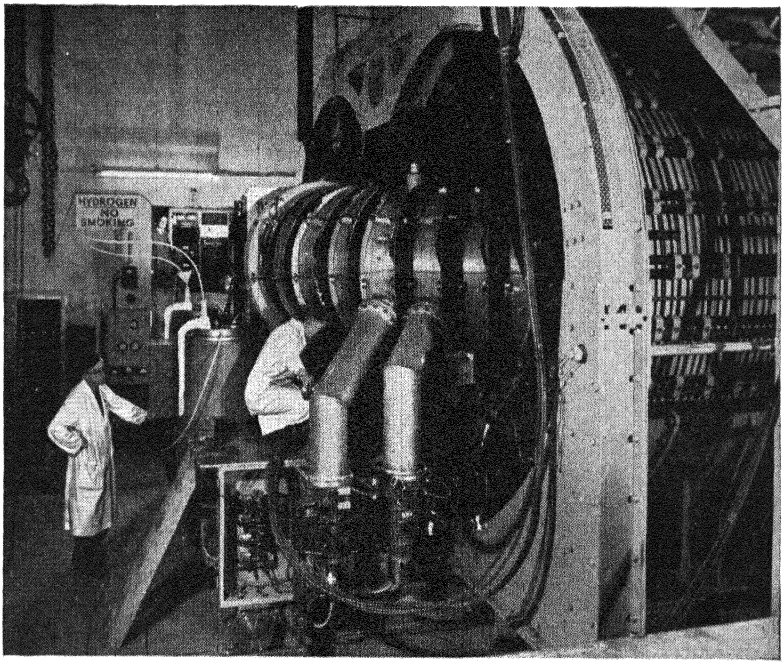
In both stages in the reaction a deuterium nucleus is ruptured, and a large amount of energy is given out.

The difficult part of the operation is to get a high enough temperature to set it working, and this has now been done by the use of magnetic fields.

If a small electric current is passed through a tube containing heavy hydrogen the gas becomes ionized. If another and much larger current is then passed through the gas magnetic forces come into action which will cause the heavy hydrogen ions to draw away from the walls of the tube and bunch themselves very closely together in a column down the middle. This compression causes a very rapid rise in temperature of the gas. In the experimental hydrogen reactor, *Zeta*, built at Harwell a temperature of 5,000,000°C. was reached, and in later models much higher temperature—100,000,000°C. and over—may be possible. At these high temperatures the deuterium ions fuse, and both radiant heat and neutrons are given out. (The hot gas itself is well away from the sides of the tube, so the tube is not affected.) The radiant heat can be absorbed by a jacket of liquid round the tube and the hot liquid could be used in a heat exchanger to generate steam and so work turbines. The neutrons could be absorbed by an outer jacket containing uranium 238 which would then be converted into the valuable atomic fuel, plutonium, or they could be mopped up in some other way.

Many scientists predict that it may be only a few years before this method of obtaining nuclear energy will be of greater importance than the 'fission' type of reactor.

Yet another possible method of fusing hydrogen atoms for the large-scale production of power may result from some experiments made in 1956 by Professor L. Alvarez of the University of California. It involves mesons—the small particles which have been observed in the atmosphere as a result of the action of cosmic rays from outer space. Mesons, as has been said already, can also be made in various ways with the help of large accelerating machines, and they may be positive, negative, or neutral. The particular mesons used in Alvarez's experi-



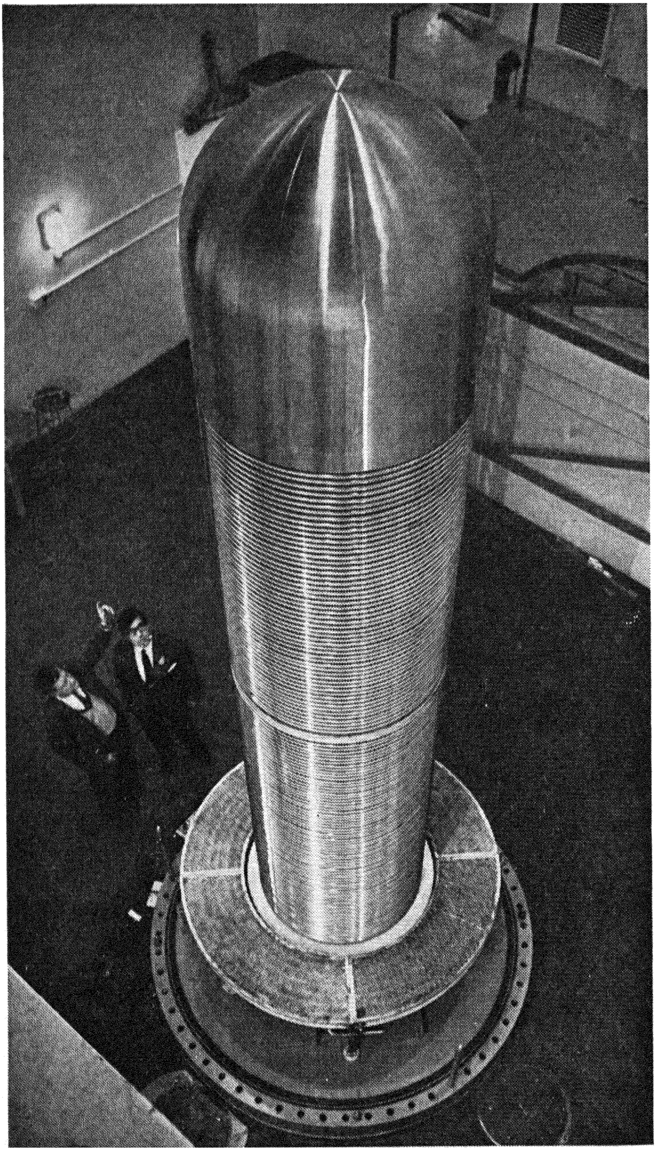
Zeta

ments are a negative kind; they weigh rather more than 200 times as much as an electron.

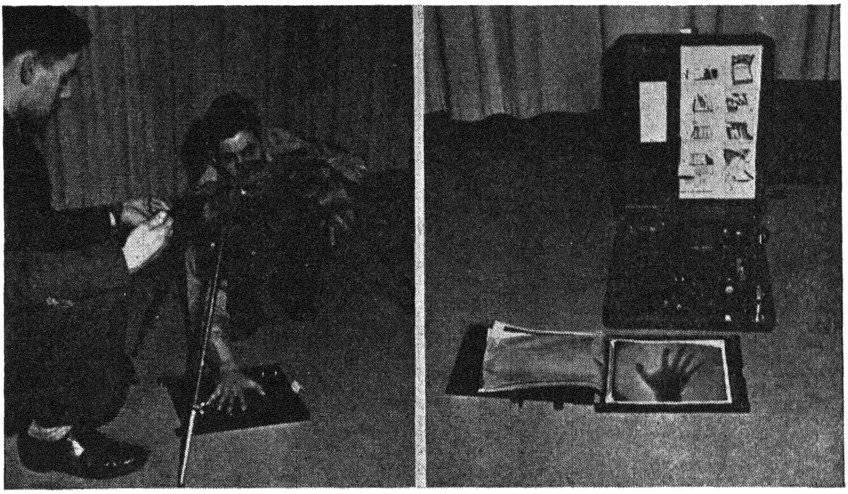
It is possible to replace the electron in a heavy hydrogen atom by a meson, but as the meson is so much heavier its orbit is very much smaller than the electron's. In fact, its distance from the nucleus is about one two-hundredth of the distance of an electron from the nucleus. Since the outside of the whole atom is, in effect, the orbit of the outermost negative particle, this makes the mesonic hydrogen atom two hundred times smaller than the normal kind.

If another heavy hydrogen nucleus now comes along it is attracted by the negative charge of the meson, though repelled by the positive charge of the nucleus in the middle of the mesonic atom. But the two forces cancel out until the approaching nucleus gets right up to the meson—in other words it gets 200 times nearer to the other nucleus than is possible with the ordinary type of hydrogen atom. Apparently this is close enough for an occasional fusion to take place.

The meson itself takes no part in the fusion; it should now be available for attachment to another heavy hydrogen nucleus to enable that also to fuse. In practice, however, it probably dies before it has a chance of assisting in another reaction, for the average life of this kind



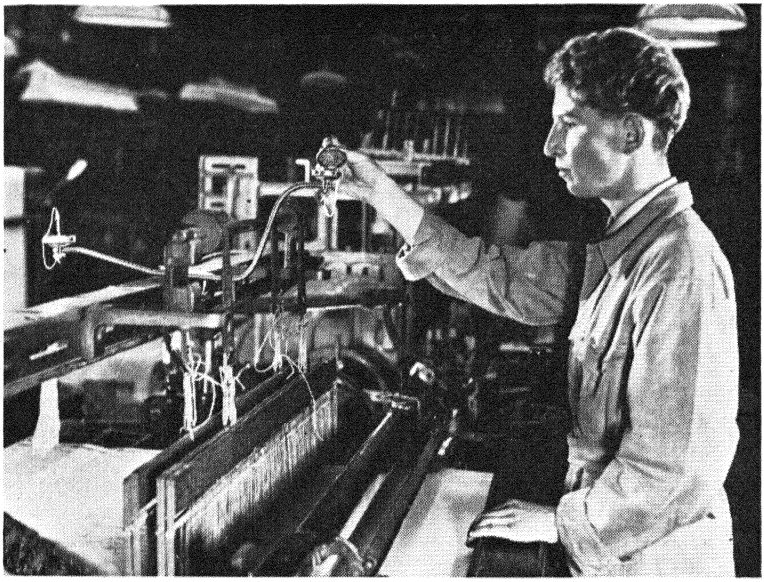
A Van de Graaf electric generator used for producing very high voltages needed in atomic research



Portable atomic X-ray unit, using Thulium capsule (*compare p.* 20)

them irradiated with particles from an accelerating machine instead. Further heat treatment can then turn them yellow, if that is the colour you prefer, or even brown. The diamonds become slightly radioactive themselves in the process, but this soon wears off, and they are then perfectly safe to wear. This particular use for atomic radiation is unlikely to have any far-reaching effect on people concerned with the diamond trade or on anyone else. After all, most people lucky enough to own them prefer their diamonds colourless—there is a feeling of something artificial about a coloured diamond.

But atomic radiation can, and often does, have far more useful effects than this one. For example, certain plastic materials can be changed in such a way that some of their physical properties alter. Take polythene, for example—the plastic material which has so many household uses as bowls, bottles, containers, and wrappings. Polythene normally has a rather low melting point, but if it is irradiated the melting point can be raised by 100°C or more. Polythene beakers, which have an increasing importance in laboratory work, can now be treated so that they can be heated over a gas flame without melting. This also may have an important application in the electrical industry; polythene is a good insulator, and for that reason is a suitable covering for electric cables; the high temperature which is sometimes reached in the wire may melt ordinary polythene, but irradiated polythene can stand up to a much higher temperature without being affected. Polythene tubing may also come to replace metal pipes for use in domestic plumbing. It is already being used for some cold-water systems—irradiated



Radioactive static eliminator on loom

polythene could be used safely for hot water pipes as well.

MAKING THE AIR A CONDUCTOR

Radiation from a radioactive chemical has the effect of making air and other gases conduct electricity; this property is of great importance in those industries where electric charges develop as the result of friction. If you rub a piece of dry brown paper with a stiff dry brush you give it an electric charge—it will, for example, stick to a wall. Electric charges of this kind are often a great nuisance in the paper-manufacturing industry. The dried paper undergoes a certain amount of friction as it passes between rollers and over moving belts, and an electric charge is built up. If the air is dry the charge cannot leak away, there is always a risk of electric sparks and therefore fire if the charge should become too great. But a small amount of a suitable radio-element placed near the paper will cause the air to become a conductor, and the charge can leak harmlessly away as soon as it is formed.

There are similar uses for radio-elements in the textile industries. Not only can danger of fire be done away with, since the charges developed when the looms are running can be led away, but the looms can be made to work faster. Also, since the individual fibres tend to stand out from the charged fabric like the hairs from your head when you brush it vigorously, anything which causes the charge to leak away also produces a smoother textile. Another important use s the elimination of 'fog marks'; anyhing with an electric charge tends to ttract small particles of dust from the ir, and at one time, when the looms topped for the night, there was always a irty grey mark over the exposed piece of abric the next morning which was exremely difficult to wash out. This 'fog ark' can now be avoided by placing a adioactive material near the loom to ake the air a conductor and so lead the harge away.

LIGHT FROM ATOMS

Another effect that radioactivity can ave on certain chemicals is that it can ake them glow. Fluorescent chemicals f this kind have long been used in the ighting industry; in mercury vapour amps, for example, a fluorescent chemial is made to glow by the action of the invisible ultra-violet light produced when the electric current passes through the mercury vapour. If a small amount of a radio-active material is mixed with the fluorescent chemical both the mercury vapour and the electric current are unnecessary; the rays from the radioactive material have the same effect as the ultra-violet light. The radioactive material chosen for a lamp of this kind can be one where the rays are not very penetrating, and this means that the fluorescent chemical will last longer than when it is bombarded with other kinds of radiation.

RAYS IN INDUSTRY

The different penetrating powers of the various forms of radiation given off by radio-elements have important applications in many factory processes. The thicker a material the less radiation will it let through. In a steel-rolling mill, for

Testing paper for regularity with a Thulium 204 *profile unit* example, the thickness of the steel strip can be continually measured by having a suitable radioactive source on one side of it and a detecting instrument, such as a Geiger counter, on the other side. As the steel strip passes along its thickness is measured all the time by the amount of radiation it lets through. A similar instrument works on the reflecting principle—for example, the thickness of the skin of tin on a piece of tin-plate can be measured by passing rays through the tin; they are reflected back from the layer of steel underneath and their intensity measured on a detector. The intensity varies, of course, with the thickness of the tin coating.

Other thickness gauges are used to test the amount of tooth-paste in a tube, the height of a detergent powder or of cornflakes in a packet, the amount of tobacco and the tightness of its packing in a cigarette, or the level of a liquid in a boiler or other container. The reflecting method, on a very large scale, is also used in prospecting for oil. Rays from a fairly powerful source can be sent down into the earth and reflected, in various degrees, from different layers of rock beneath the surface. (This is similar in principle to the echo-sounding method of prospecting which has been used in the oil industry for some time.) Reflection of a special type will tell the expert if an oil-bearing layer is present.

A rather similar principle is now being used in the coal industry for sorting coal from shale. A mechanical sorter, which makes use of the difference in density between the coal and shale, may cost up to half a million pounds. It is now possible to make use of a radioactive method of sorting; a radioactive isotope, Thulium 170, gives out X-rays of a rather low intensity. These are scattered more by the lumps of coal than by the lumps of shale, and by picking up the scattered rays on a suitable detector an automatic sorting apparatus can be brought into action.

One of the most important uses for very short wave light radiation is for taking X-ray photographs. The conventional kind of X-ray machine is still used in hospitals and for taking X-ray pictures of, for example, the steel components of machines to see if there have been any faults in the casting. But radioactive elements that give out γ-rays—which are simply very penetrating X-rays—can be used equally well in a number of processes. One very ingenious method is to mix a very little radioactive gold with the material used in the manufacture of articles such as telephones. The article then gives out its own radiation and can take its own photograph, showing if there are any flaws in the material.

A rather different method has been developed for taking X-ray photographs of welds, for example, in tubes of fairly narrow bore, or in boilers where the entrance aperture is very small. The radioactive source on the end of a rod can be pushed right inside the tube or boiler, and if a photographic plate is fastened over the weld on the outside the rays will cause a photograph of the weld to be taken on the plate. In this way flaws can be found which would otherwise be undetectable. A process of this kind is now being widely used for the checking of oil pipelines in many different countries.

gets concentrated in the thyroid cells, even though some of these may have wandered to other parts of the body. So if a patient with this disease is given large doses of *radioactive* iodine, the iodine becomes concentrated in the diseased cells, and as its radiation is naturally much stronger there than anywhere else the diseased cells are destroyed while other parts of the body are unaffected. The dosage has to be carefully controlled, of course, or the whole of the thyroid might be destroyed; but this can be done, and many patients have been cured by this new treatment.

Unfortunately there are not many parts of the body that absorb one particular element selectively as the thyroid does iodine, but occasionally a certain type of brain tumour can be treated with radioactive arsenic in this way, and as time goes on doctors are almost bound to discover new ways of directing the lethal rays at diseased parts of the body.

Human body cells are not the only cells to be destroyed by radioactivity. Germs can also be 'shot dead' with a radioactive isotope, and this method could be used in hospitals for sterilizing blankets, for example, which often shrink very badly when treated in the usual steam sterilizer. Antibiotics, such as penicillin and streptomycin, might also be sterilized in this way—also vaccines used to protect people against such diseases as smallpox and poliomyelitis.

RAYS FOR PRESERVING FOOD

The lethal effect of the rays given off by radioactive elements is already being used on an experimental scale in preserving food. In order to kill *all* bacteria rather heavy doses of radiation have to be given. But to make the bacteria infertile—that is to make them incapable of reproducing themselves—much smaller doses are sufficient. Research is still going on in this subject, but it already seems that meat and milk and other animal products can be safely preserved by irradiation, and that although their taste may be altered a little, there are no harmful effects on the foods.

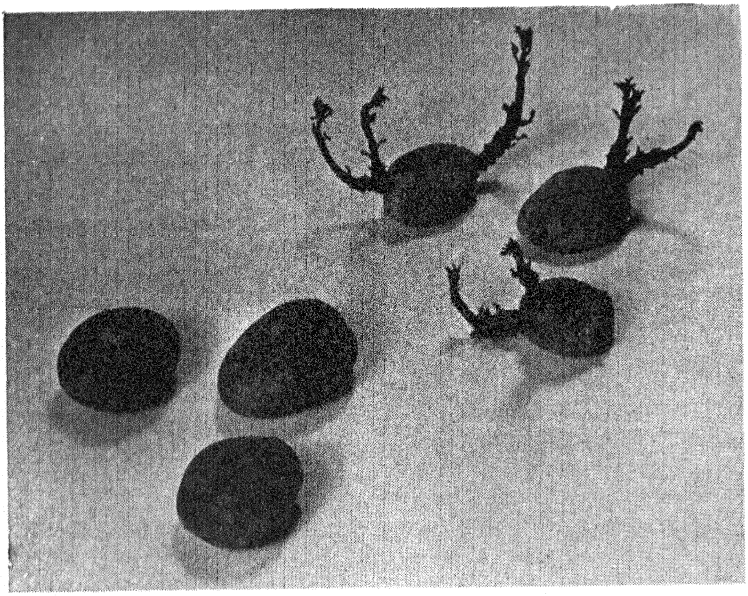
Another interesting use of radiation is in preventing the growth of plant tissue. If potatoes are stored all the winter nature will see to it that they begin to sprout in the spring, which makes their value as food much less. But if they are given a small dose of radiation they will not sprout, and this may prove to be a very valuable way of prolonging the time in which they can be stored without deterioration. A similar result has been obtained by irradiating onions.

THE SCREW WORM FLY

One of the nastiest little pests in many tropical countries is an insect known as the screw worm fly. This creature lays its eggs in open wounds on horses and cattle, and the grubs that hatch out eat their way into the flesh and may even kill their host.

Now X-rays, if they are intense enough, may cause death; but almost as important is the fact that less intense rays can make certain insects sterile—that is, they are able to mate in the usual way, but the eggs that are laid as a result of the mating are incapable of hatching out.

Obviously it would be impracticable to try to kill all the screw worm flies in a given area by radiation, so the second effect is used.



Potatoes (*left*) *that have been irradiated to prevent sprouting. Those on the right are untreated*

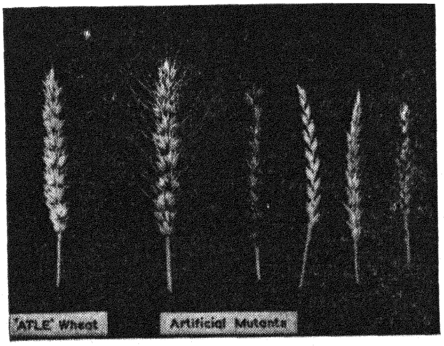
Biologists have found that female screw worm flies mate only once in their lives. If male screw worm flies are bred in captivity and then irradiated they will become sterile. If they are now released in large numbers, many of them will mate with the female flies occurring wild. So a vast proportion of the eggs laid by the females will be infertile. This means fewer flies in the next generation, and if the experiment is repeated, sooner or later there will be no wild females to carry on the species. This was the method used by American scientists in the island of Curaçao. This island was once one of the worst breeding grounds for the screw worm fly. Then huge numbers of irradiated male flies were dropped from aircraft and within a very short time the whole island of Curaçao was freed from this troublesome pest. Similar experiments are being carried out in the southern parts of the United States.

RAYS HELP THE FARMER

A large dose kills; a smaller dose kills the reproductive cells; a smaller dose still may cause changes in the reproductive cells though it does not destroy them. This last effect has been used recently in plant breeding.

When plant breeders wish to improve the strain of a particular plant, such as wheat, one of the things to do is to keep a look out for individual plants which may show better qualities than the general strain. Of course, a plant may be better than its neighbours simply because it is growing on better ground, but the scientists make sure that all the plants they wish to compare are treated alike. If enough are grown there will usually be one or two of these improved *sports* or *mutants*, as the scientist calls them, in each generation. If these are isolated they will 'breed true'—that is, the plants grown from their seeds will be like the rather different parent plants rather than like the general strain. Crosses between old and new strains may produce even more useful varieties. In this way many new strains of food-crops, such as oats or wheat, have been developed by plant breeders.

This much has been going on for many years, but scientists have now found that if the seeds or pollen of a plant are irradiated there are many more mutants in the next generation than there would be if things were just left to nature. There is no means of controlling the mutants—some may be no good to the grower, others may combine some favourable characteristics with some unfavourable ones. But among the large number produced, some of the mutants may prove to be an improvement on their parents, and many new varieties that have been found in this way are now being grown on a larger scale. There is a kind of barley, for example, which has shorter sturdier stems than the old kind—very useful for growing on a large farm where there is little protection from the wind. A new form of oats resistant to the fungus disease known as 'rust' has proved most successful in the United States.



Artificial mutants of 'Atle' wheat

A new kind of peanut, another radiation mutant, bears a thirty per cent greater crop than its parent. Improved varieties of other crops have been evolved, cereals that mature earlier, for example, and various plants resistant to such diseases as leaf blight.

On an experimental scale interesting new colours have been induced by irradiation in some flowering plants; perhaps some day we shall have an atomic sky-blue rose or an atomic black daffodil.

ISOTOPES AS TRACERS

Quite apart from the effect that their radiation has on altering the properties of both living and non-living material, radioactive isotopes used as 'tracers' are of increasing importance in industry, medicine, agriculture and other applied sciences.

If you imagine yourself flying in an aeroplane on a very dark night over a large field containing a million men all dressed in black, and somewhere among them a Mr. Jones, you would find it impossible to pick out Mr. Jones as an individual. But if Mr. Jones were carrying a flaming torch you would now see a pin-point of light that would tell you where in the field Mr. Jones was.

This is how a radioactive tracer works. For example, the Port of London

Authority wanted to know about the movements of silt on the bed of the river Thames, a matter of great importance for shipping. It is impossible to find out exactly how the silt on any one part of the river bed gets there simply by sailing over it in a boat. Yet if some of the silt were giving out rays that could be detected, the movements of that silt could be followed. So the scientists ground some glass containing the metal scandium into a fine powder with particles the size of the silt particles. This artificial silt was then irradiated in an atomic pile, and the scandium was converted into a radioisotope which gave off intense gamma rays. The glass was then mixed with some silt dredged up from the river bed, and the mixture was dumped in the Thames at Gravesend at high tide. As the tide flowed out the movement of the silt was followed with the aid of under-water Geiger counters.

At first the silt moved down-stream with the tide, as might have been expected, and it would seem reasonable to suppose that it would continue to move downstream because of the pressure of the fresh water flowing down the river. Yet, a few weeks after the experiment, radioactivity was found coming from the silt on the river bottom at Barking, fourteen miles up-stream. It was found, as a result of these experiments, that five times as much silt is carried up-stream by the incoming tide as is carried downstream by the river. This information is of great importance when dredging operations are being planned.

These are similar problems in many estuaries where movements of sand caused by tides and currents can cause serious blockage of shipping channels. These movements are now being studied by 'tracer' methods, and so is the wearing away of land by the sea on many parts of the coast. The more that is known about these changes the more likely it is that scientists may be able to find ways of controlling them.

METAL FOR TRANSISTORS

Radioactive tracers play an important part in detecting impurities in materials used in industry. The transistors used instead of valves in scientific instruments —in very small radio-sets, hearing aids and electronic computors, for example— depend for their efficient working on the purity of the semi-conducting metals of which they are made. One such metal is germanium. It is very difficult to detect minute traces of impurities in germanium by ordinary chemical analysis. But if a very small amount of a radioactive element such as indium is mixed with the molten germanium and then the germanium allowed to grow as a crystal 'pulled' from the molten metal, it is found, by moving a Geiger counter along the length of the crystal, that all the indium impurity is concentrated at the tail end of the crystal. From experiments of this kind the whereabouts in the crystal of any naturally occurring impurity can be found, and only the purest parts are then used for the transitors.

MEASURING WEAR AND TEAR

In many branches of industry it is important for manufacturers to know the rate at which moving parts of machines may be expected to wear. This particularly applies to processes involving

Measuring piston wear

machine tools in metal working industries. Until recently the standard tests for measuring the rate of wear of a particular cutting tool might take up to a month. Expensive drilling and mining operations were involved, and very often the tool had to be used continuously until it wore out before the rate of wear could be measured at all accurately.

The new radioactivity method of testing takes only 24 hours. First the cutting tool itself is made radio-active by neutron irradiation in an atomic reaction. Then it is allowed to machine a piece of metal for perhaps half a dozen trial runs, each lasting only ten seconds. The chips cut from the piece of metal are collected together, washed, dried, and weighed. Each metal chip contains embedded in it a very small amount of metal worn from the tool itself. There may be similar particles from the tool in the liquid used to cool the tool while it is running. The amount of radioactivity of the chips and the liquids is measured on a counter, and the amount the tool has worn away can be worked out.

A similar process measures the wear on pistons in engines. The piston rings are irradiated and run in a test engine for a given number of strokes. A very small amount of steel is worn off, and this is collected in the oil and its radio-activity measured. The rate of wear of the piston ring can then be calculated. It is found that it wears down faster during the running-in period, which is what might be expected anyway.

The life of a rubber tyre can also be estimated after a very small number of experimental runs. A known amount of radioactive phosphorus is included in one of the chemicals used in preparing the rubber. The tyre is fixed to the test vehicle, and a Geiger counter is towed behind to measure the radioactive bits worn from the tyre by different road surfaces at different speeds. One interesting result that has been found is that the tyre will last nearly twice as long if the vehicle is driven at 30 miles an hour as if it is driven at 60 miles an hour.

THE PERFECT MIX

Many processes—both industrial and agricultural—depend for their efficiency on very thorough mixing of materials. In the large-scale preparation of cattle food, for example, a small but essential amount of a vitamin has to be added in order to keep the cattle healthy—perhaps only an ounce of the vitamin to a ton of food. This small amount must be distributed evenly—otherwise some cattle will get too large a dose and others none at all. A small amount of a radioactive material is included with the vitamin. After the vitamin has been mixed in with the food it is a simple matter to test samples of it for radioactivity—all samples of the same weight should be equally radioactive if the vitamin has been thoroughly mixed. The radioactivity in this case is very short-lived—it dies away very quickly, and there is no possible danger to the cattle eating the food.

Similar methods can be used to check whether the ingredients of paint are properly mixed. This time the material is tested photographically. A small amount of the paint is spread evenly on a photographic plate, and if the radioactive ingredient is evenly distributed, all parts of the plate are affected equally by the rays, and there are no very dark or very light patches. In the glass-making industry small amounts of radioactive sodium, phosphorus, and barium are included in the ingredients and so the mixture can easily be tested to make sure the materials are all blended properly. The quality of the glass is affected by uneven mixing, and as a result of experiments of this kind a new type of tank has been developed for glass-making.

TRACERS IN THE METAL INDUSTRY

A slightly different problem has been tackled in a similar way in the iron industry.

Iron is made from various grades of iron-ore in blast furnaces. In low-grade ores the powder is very fine, and there was some doubt whether it was all being smelted efficiently, or whether some of the fine powder was being blown right out of the furnace by the blast of air passing through. So five pounds of the powder were made radioactive in a nuclear reactor and mixed first with 22 tons of untreated powder and then with 54 tons of the higher grade coarse ore. After the ore had been smelted the degrees of radioactivity in the pig iron, in the dust blown out in the blast, and in the slag were measured. It was found that only about sixty per cent of the fine ore was converted to pig-iron. As a result of this experiment research is now being carried out to find a practical way of getting the small particles to stick together to form larger ones that will not be blown away.

There are many other uses for radioactive tracers in the metal industry and in metallurgical research. Quite often it would be impossible to discover what was happening without the use .of tracers. The diffusion of one metal into another is an example. Gases diffuse into each other very quickly; their particles are moving about freely, and there is no force to stop them wandering between each other, so that the air, for example, is a pretty uniform mixture of the various gases it contains. Solutions of salts and many other liquids also diffuse into each other, but more slowly. It might be thought that solids cannot diffuse at all; but if a perfectly flat block of iron is left in close contact with a similar block of copper, after some months it is possible to detect by chemical means that some of the copper particles have 'wandered' into the iron, and that some of the iron particles have wandered into the copper.

But if the two blocks are both of the same metal, it would obviously be very difficult to tell whether any particular particles of metal had been there from the start or had emigrated from the other block. This is where radioactivity comes in. If, for example, the research metallurgist wants to know how quickly solid tin diffuses into solid tin, all he has to do is to make one of his blocks radioactive by irradiating it in an atomic pile, and leave the two flat surfaces in contact with each other. If the untreated block is afterwards found to be radioactive, obviously some of the radioactive tin atoms must have 'wandered'. By this method not only have scientists been able to find out that diffusion of one particular metal into a second metal does take place, but they have also been able to draw a 'map' of the wandering particles. They find, for example, that in the case of tin the atoms that penetrate the second block tend to follow definite paths according to the structure of the tin crystals.

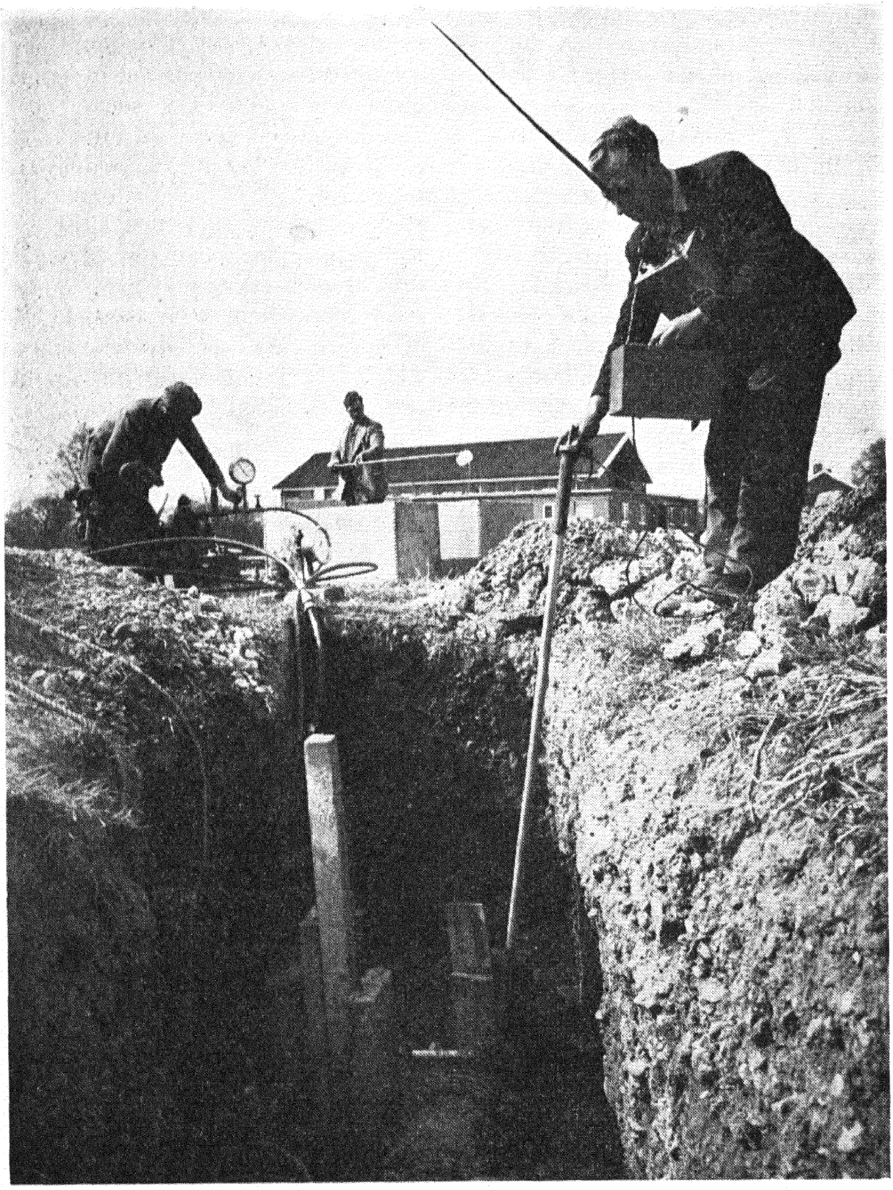
A great many pieces of scientific research of this kind may appear, on the surface, to have little use to anyone, yet it is by such experiments that scientists are able to discover why metals may change their properties with time, and this has an important bearing on engineering, where the strength of metals is of the greatest importance.

DETECTING LEAKS

Radioactive isotopes have been used extensively in detecting possible leaks in pipes and tanks. For example, when a Comet aircraft crashed for no apparent reason, various possible causes of the disaster were investigated by experiments on similar aircraft. One suggestion was that there might have been a fuel leakage, so the fuel was 'labelled' by adding a little radioactive palladium to it and the aircraft was put through all kinds of aerobatics. The surface of the aircraft was then examined with a Geiger counter to see if any part of it had become radioactive. No radio-activity was detected, and it was thought extremely unlikely that a fuel leakage had been the cause of the crash.

Leaks in water pipes are often very difficult to find. In Glasgow, for example, where many of the water pipes are very old, about half the water sent through the city was being wasted through leaks. The engineers worked out that it would cost more to find out where all the leaks were by the old methods than the value of the wasted water. But now that radioactivity can be used the process of detecting is much cheaper.

There are various methods that can be used. One is to mix a little sodium bicarbonate solution containing radioactive sodium with the water and run it through the water system; the water is afterwards cut off and the ground examined with a Geiger counter. The leaks can then be found and mended. The radioactivity of the sodium decays very quickly, so there is no possible danger of contaminating the water supply when it is turned on again. This method may not always be convenient in practice, especially if the course of the pipes is a long one, since it means going over the entire length of it with the counter.



Testing for leaking mains with a Geiger counter

THE 'GO-DEVIL'

Another very ingenious method has been used both for water pipes and for oil pipes. This time the exploring is automatic. If it is an oil pipe the oil is first emptied out. Then the radioactive solution is passed through it and some, of course, finds it way out through the leaks into the ground. The pipe is then thoroughly rinsed out. Along the length of the pipe, at fixed intervals above ground, small pieces of radioactive cobalt are placed, so anything travelling along the pipe itself will pass various radioactive milestones on the way, some of them the known cobalt sources and others the unknown leaks.

In order to detect these sources the engineers use a piece of apparatus known as a 'go-devil'. It is small enough to pass along the inside of the pipe and it contains, inside a water-proof casing, a Geiger-counter and a small tape-recorder. The water-flow is then started up again and the rush of the water carries the go-devil along with it. Every time the Geiger-counter passes a source of radioactivity it clicks, and the series of clicks is automatically recorded. When the go-devil comes out at the other end the tape is played back, and since the positions of the cobalt sources responsible for some of the clicks are known, the positions of the leaks corresponding to the rest of the clicks can be mapped out. This means that the engineers do not have to waste their time testing miles of sound pipeline.

ATOMS IN THE OIL INDUSTRY

There are many other uses for radioactive isotopes in the oil industry. The same oil pipe-lines are often used to deliver various grades of oil, and a small amount of a radioactive element introduced as a marker at the dispatch end of the pipe will show, at the delivery end, when one grade of oil finishes and the next begins, so the receiving tanks can be switched over. Radioactive isotopes can also be used to explore oil-wells, and to follow the path of the oil-flow through the maze of pipes in an oil-refinery. It has been estimated that millions of pounds have been saved in this one industry by the use of radioactive materials.

ATOMS FOR HEALTH

Perhaps the most valuable use for radioactive isotopes is in the detection and prevention of disease. One serious cause of unhealthy conditions, both in buildings above ground and in underground structures such as funnels and mineshafts, is poor ventilation. If a little radio-active gas is released into the air, the rate at which it disappears, as measured on a Geiger counter, shows quickly and simply how good the ventilation is.

Even more impressive is the use of radio-isotopes in hospitals. One of the most important uses is in surgery. A little radioactive sodium, in the form of sodium chloride (common salt) can be injected into the patient's blood-stream. (The radioactive sodium quickly decays, so no permanent harm is done to the body.) In the case of a skin-graft, for example, the surgeon can quickly tell whether the graft has 'taken' by following the passage of the radio-active sodium with a Geiger counter. If the graft is all right the blood should flow from the patient's body to the new skin. Another example is the very rare and difficult operation for the separation of Siamese twins. In one case the twins were joined in the lower part of the body, and before he could operate the surgeon wanted to know whether there were blood vessels in the join carrying a supply of blood from one twin to the other. The radioactive salt gave him the answer.

Another use for radioactive salt is in measuring the rate of flow of blood along damaged veins or arteries, and yet another is in measuring the total volume of blood in the body; a known volume of salt solution is injected into the blood and allowed to circulate until it is thoroughly mixed; if an equal quantity is then drawn off and its radioactivity measured, it is easy to calculate how much the original amount has been diluted, and therefore the total volume of the blood.

The use of strongly radioactive iodine for killing diseased thyroid tissue has already been mentioned; a less drastic dose is very useful as a tracer for telling the surgeon exactly how big a thyroid gland is. It takes only a few hours for iodine swallowed in a glass of water to become concentrated in the thyroid. By passing a small Geiger counter in a series of parallel paths over the site of the thyroid an exact 'map' of the gland may be made and recorded automatically on paper.

Teeth and bones contain a lot of calcium, and by adding a small amount of radioactive calcium to foods containing a known amount of the ordinary kind, the rate at which the calcium is absorbed by these parts of the body can be calculated. It is found that practically all the calcium taken in by the body is absorbed in about eight hours.

TOUGH EGGS

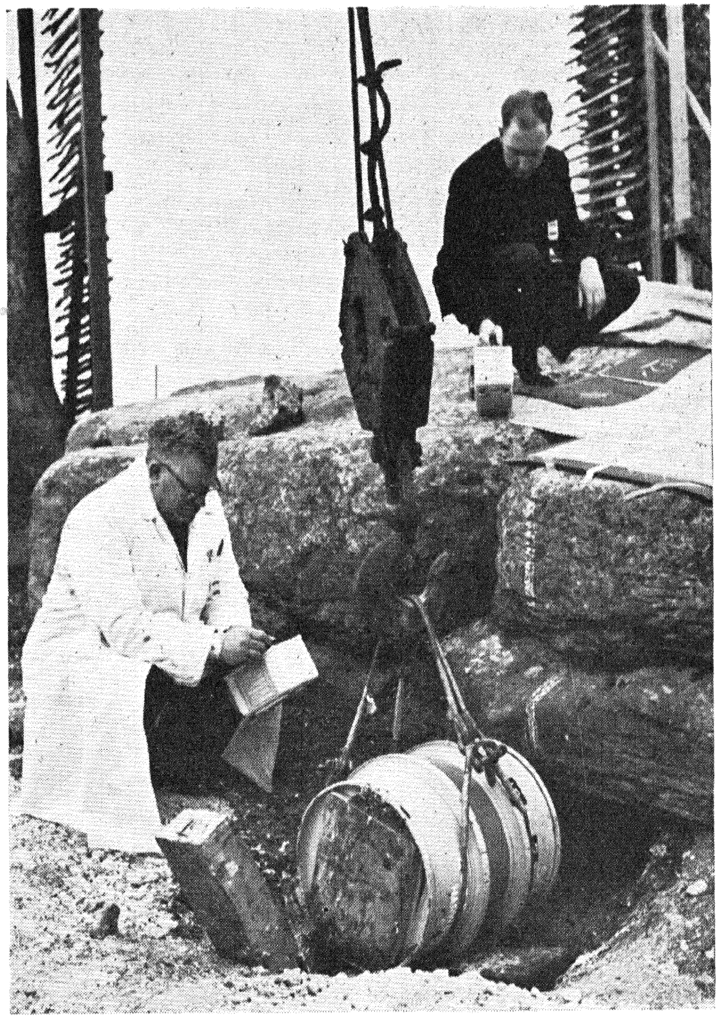
A similar use for radioactive calcium is in agricultural research. Egg-shells contain calcium, and by feeding a small amount of radioactive calcium to hens, the rate at which the calcium is absorbed for eggshells can be found. Nearly half the calcium given to a laying fowl is found to be deposited in the egg-shell twenty-four hours later. Obviously, then, laying fowls need a constant supply of calcium—a specially large dose once a week won't do. This has an important bearing on large-scale poultry farming, for where millions of eggs are involved, very thin eggshells (which are broken easily) may result in the loss of a great amount of money.

ATOMS FOR PLANTS

Modern methods of food production depend to an increasing extent on the application of fertilizers to the land. It is obviously important for farmers to know how and when to apply these fertilizers.

Until recently it was thought that the leaves of plants were responsible for taking in all the carbon the plant needed—as carbon dioxide from the air—and that the roots of the plant, and only the roots, took in everything else.

Growing plants need a great many different elements, but the three chief ones necessary to add to most fields on which crops are grown are nitrogen, potassium, and phosphorus. The path of radioactive phosphorus, added to different parts of the soil and taken in through the roots of a plant can be traced out with a Geiger counter. It has been found that a lot of the phosphate fertilizer normally added to the soil is washed away by the



Stonehenge X-rayed. Before one of the fallen uprights of Stonehenge was raised in 1958 *an X-ray photograph was taken to show the depth and extent of the cracks in it. A three-inch cylinder of Sodium-*24 *was enclosed, for safety, in the one-ton drum of lead seen above, and pulled out by a wire from the far side. A* 36*-hour exposure provided a print on the sensitized paper taped down to the stone, and showed that the stone could safely be moved. Note the Geiger counters.*

rain before it can be used. More efficient methods of applying the fertilizers can therefore be worked out. It has also been found, by applying radioactive phosphates to the leaves of plants, that under certain conditions some plants are able to take in phosphorus through their leaves; in fact, it has been said that phosphate fertilizer given in this way may be nearly ten times as effective as when it is applied to the soil. This result was wholly unexpected, and it may make a vast amount of difference to the money spent on fertilizers in the growing of such crops as tobacco and wheat. Another unexpected result of tests using radioactive carbon was that this element, in the form of carbonic acid, was found to be taken in by the roots of plants as well as by the leaves. So the addition to the soil of organic manures—that is, decayed plant and animal material containing carbon compounds—may well be of far more importance to the plant in this respect than many scientists had believed possible.

A number of these applications of radioactive tracers to agriculture have already resulted in the saving of millions of pounds; but there are many other possible uses, some of them still being explored by the research worker. For example, every year dozens of new chemicals are prepared and tried out for their possible use as insecticides and fungicides. Only a small number of them ever find their way on to the market, but they all have to be tested. The old way was costly and laborious and took a considerable time. Now, by 'labelling' the chemical with a radioactive element, its effectiveness can very quickly be traced.

Forestry is another subject that has benefitted by the use of radioactive isotopes. If a fertilizer containing a radioactive tracer is fed to one tree, in an oak wood for example, it is very quickly found in neighbouring trees as well. The reason is that the roots of the trees, criss-crossing and touching each other in the soil, become firmly grafted together—just as a cultivated rose may be grafted on a briar stock. In fact, a dense oak forest may be not just a collection of individual trees but one living organic whole, for every single tree may be joined to its neighbours in this way. This means that the trees may share their food materials, and this result may obviously be of benefit to the forest as a whole. But it also means that they will share disease viruses as well, and these may spread from one tree to others through the grafted roots at a very fast rate.

So far this work is mainly in the research stage, but once scientists have understood the causes of some particular effect they are much more likely to be able to find a way of controlling it.

ATOMS AND PESTS

Most gardeners know from experience that if the soil on their allotments contains pests such as wire-worms these creatures will almost invariably find their way to the foot they enjoy, in this case potatoes and carrots. Yet until recently nobody knew just how far a wireworm could smell out a potato in the soil. Scientists caught some wireworms and attached to each a small amount of radio active material. They then let one loose in a confined area of soil containing one potato. The speed with which the wireworm detected the potato was found by following its travels with a Geiger counter. Beyond a certain distance its movements were apparently random. Then, if it happened to come within a fixed radius of the potato it obviously sensed it, and made a bee-line in the right direction.

Here again, the knowledge of how something works may easily lead to a method of control of a tiresome pest.

Even more harmful than wireworms are disease-carrying insects like houseflies and mosquitoes. The distance one of these insects can fly has an obvious bearing on the speed with which it can carry a disease. Both flies and mosquitoes have been 'labelled' in order to find out how quickly they can spread out from a given point. This knowledge may be very important, especially in tropical countries where the spread of insect-born disease is very rapid.

CONCLUSION

How many useful ways of using radioactive materials have been mentioned in the last 20 pages? Count them up and see. But these examples form only a fraction of the present number of ways of using radioactive isotopes —apart from uses at present un-thought of.

Very little has been said in this book about the destructive uses of atomic energy. But we should be fully aware of the possible dangers to health by the freeing into the air of vast amounts of very highly radioactive materials from atomic bomb tests—apart from the threat of wiping out whole sections of the human family, possibly the entire human race, by the use in war of such frightful weapons. There is plenty about these subjects in the press and everybody, young and old, should make it his business to know about such things and to try to understand them.

If only man can overcome his extraordinary desire to kill other people the knowledge the Atomic Age has brought him can do untold good to the whole human race. Problems, at present apparently insoluble, of the prevention of certain diseases, problems of growing enough food for everyone to have enough to eat, problems of industry affecting our whole way of living—all these may well come to be solved with the help of nuclear energy and nuclear particles, the new tools of science, the tools given to man by the tiny, mighty atom.

A SELECT BOOK LIST

BY ELIZABETH N. BEWICK

CENTRAL OFFICE OF INFORMATION. *Nuclear energy in Britain.* (C.O.I. reference pamphlet, 28.) H.M.S.O., 1957. Map, book list. A brief survey of the development of the peaceful uses of atomic energy in Great Britain, progress in research, the part played by private industry and the nuclear power programme for the future.

CROWTHER, J. G. *Nuclear energy in industry.* Newnes, 1956. Illus., map, diagrams. A popular survey of the subject, covering the historical development of nuclear power, the choice of reactor systems, isotopes, uranium deposits and prospecting techniques. Advanced.

GAMOW, G. *Mr. Tompkins explores the atom.* C.U.P., 1955. Illus. A fantasy-story giving a semi-humorous but accurate account of the principles of modern physics.

HABER, HEINZ. *The Walt Disney story of our friend the atom.* Rathbone Books, 1956. Illus. A pictorial history of atomic research and the scientists who contributed to it, designed and illustrated by the Walt Disney Studios.

JAY, K. E. B. *Britain's atomic factories: the story of atomic energy production in Britain.* H.M.S.O., 1954. Illus., diagrams. Reviews the design, construction and operation of the factories which are needed for the manufacture of fissile material; with a brief explanation of the physical basis of atomic engineering.

JAY, K. E. B. *Calder Hall: the story of Britain's first atomic power station.* Methuen, 1956. Illus., diagrams. A report on the work of Calder Hall and how the results of atomic research at Harwell are translated into engineering reality at the power station.

JEFFERSON, S. *Radioisotopes: a new tool for industry.* Newnes, 1957. Illus., diagrams. An account of the uses of radioactive materials in modern industry, the elementary principles of radioactivity and the health precautions essential to workers in the field. Advanced.

MANN, M. *Peacetime uses of atomic energy.* Thames & Hudson, 1957. Illus. A survey for the general reader of the many and varied uses of atomic energy in the modern world, but chiefly in the United States of America. Lavishly illustrated.

RIEDMAN, S. R. *Men and women behind the atom.* Abelard-Schuman, 1957. Illus. Brief biographies of some of the scientists in England, France and America who have helped to discover the source of atomic energy and the uses of atomic power.

THOMSON, SIR GEORGE. *The atom.* ("Home University Library.") O.U.P., 5th edn., 1956. Illus., diagrams, book list. An introduction to atomic science and the uses of atomic energy.

UNITED KINGDOM ATOMIC ENERGY AUTHORITY. *Harwell: the British atomic energy research establishment,* 1946–1951. H.M.S.O., reissued 1955. Illus., book list. A report on the early research programme at Harwell and brief accounts of the original reactors GLEEP and BEPO.

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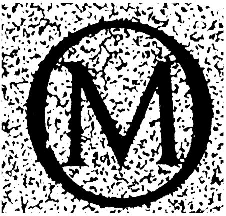
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