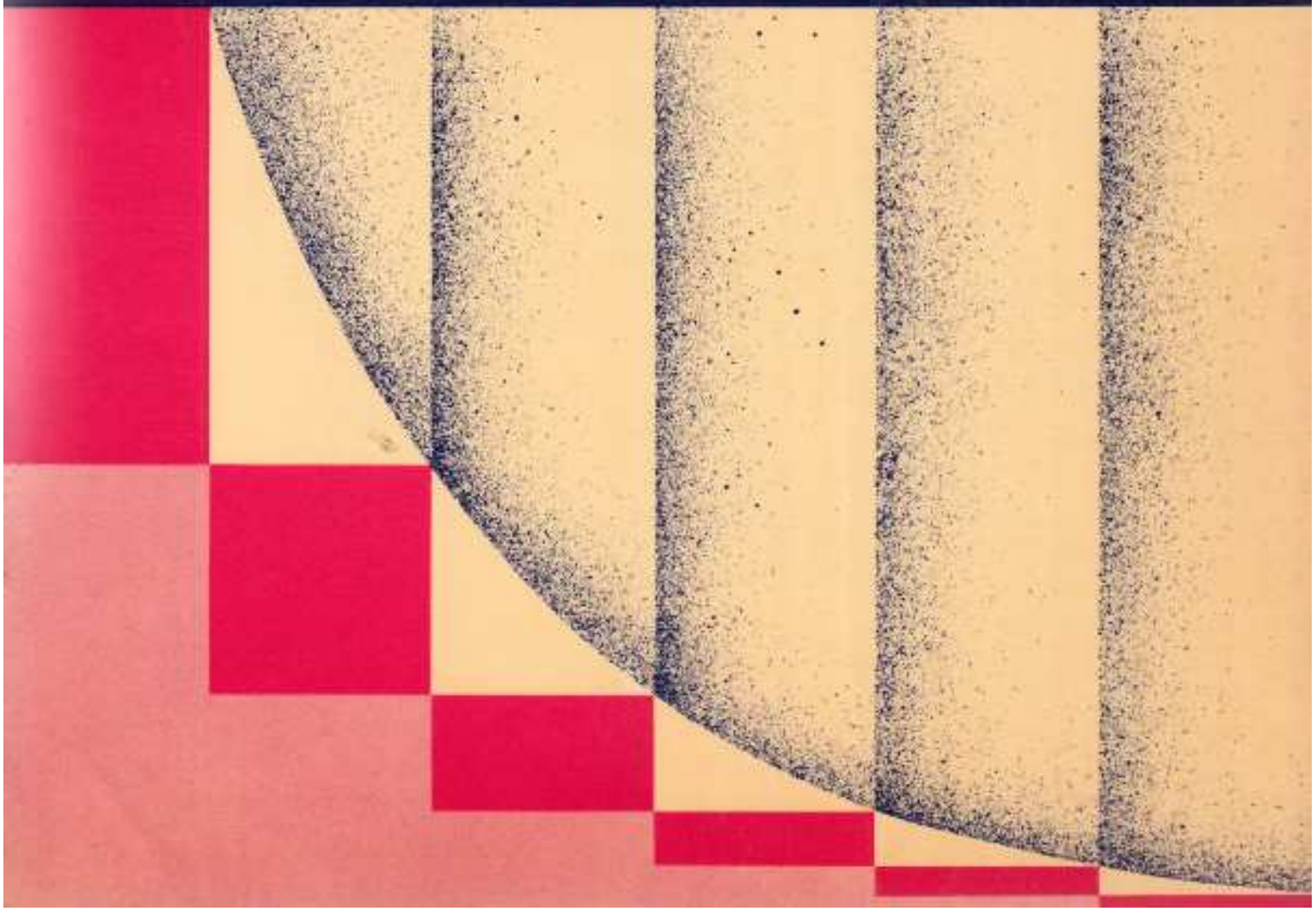
Chemistry Background Book

Radioactive Chemicals



Introduction

How radioactivity was discovered, and how this discovery led to our present knowledge of matter, is a story of scientific research mingled with lucky accident. Important and interesting too are the uses which have been found more recently for radioactive substances and their radiations as tools for research and industry: tools whose power and versatility have yet to be fully exploited.

The end of the nineteenth century saw some spectacular advances in scientific knowledge. One of the reasons for this was the great improvement in apparatus, but more important was the growth of an attitude of mind – the attitude that a theory was a thing not to be accepted as a creed, nor to be rejected as heresy, but to be taken and tested. (This was slow to come about and one cannot say it is fully accepted even today.) The development of knowledge about the structure of the atom was one of the most far-reaching advances of the period, and is the one chiefly responsible for the present-day pattern of science, in which the divisions between different branches, such as physics, chemistry, and biology, are far less rigid than they used to be. At the end of the nineteenth century several discoveries were announced which may be said to have started this unifying process.

Part 1
Some discoveries

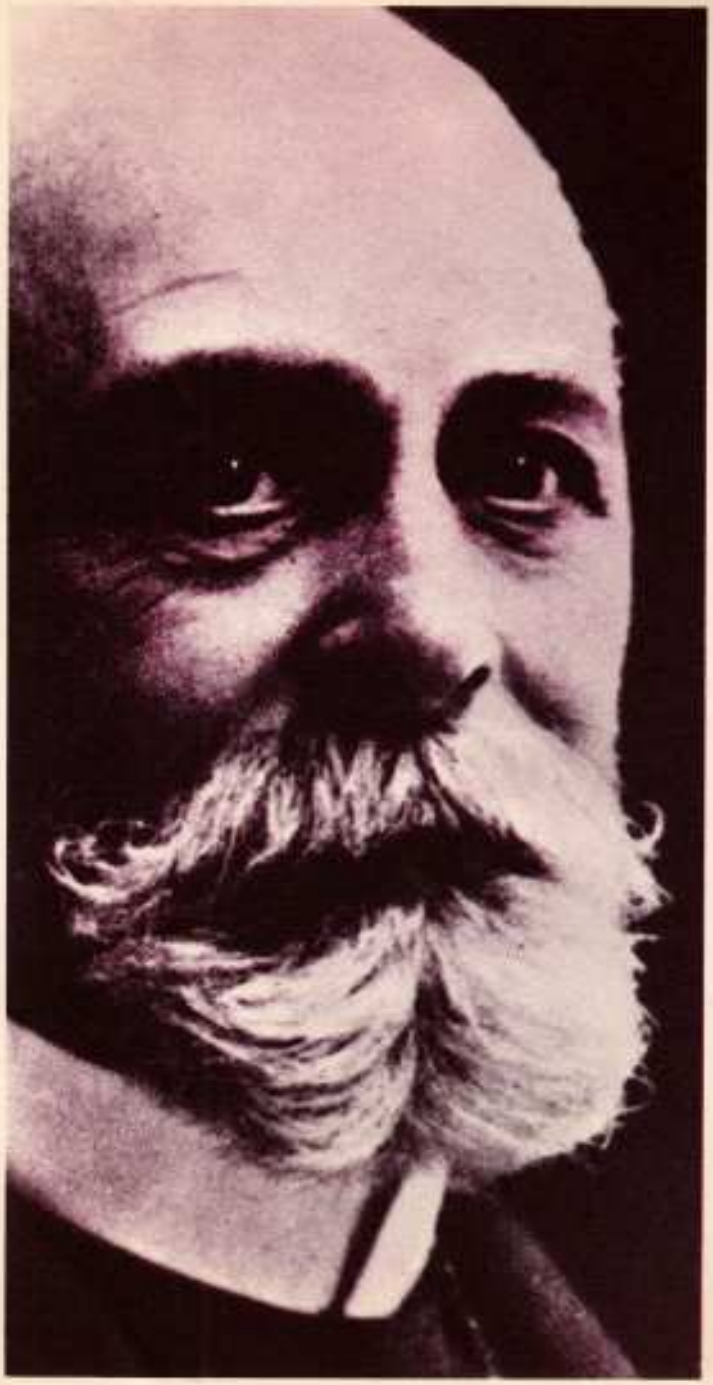
Roentgen and X-rays – We are very familiar nowadays with fluorescent substances. They make things 'whiter than white' and are used in paints on road signs and posters. Fluorescent substances emit a glow of their own when stimulated by light, and certain of them are used as a coating on the inner surface of a discharge tube to increase the efficiency of electric lighting. In 1895 Wilhelm Roentgen, a German physicist, was investigating this phenomenon and found that even when he enclosed the discharge tube in a light-tight box, crystals of barium platinocyanide placed nearby would glow brightly. Some kind of invisible rays from the discharge tube seemed to be escaping from the box and stimulating the crystals. Roentgen also found that the rays would pass through the walls of a light-tight box and darken a photographic plate. He gave these penetrating rays the name of X-rays, and used them to take X-ray photographs of opaque objects such as the hand. This discovery caused quite a stir: for instance 'X-ray proof clothing' was advertised in order to preserve dignity and modesty!

Other scientists found that when X-rays passed through air it became a conductor of electricity and, for example, a charged gold-leaf electroscope was discharged when a beam of X-rays passed between the deflected leaves. The process of making a gas conducting in this way is called ionization, and we shall have more to say about it. It took several more years to discover the nature of X-rays, but it was eventually shown that they are electromagnetic waves of the same nature as light but of shorter wavelength.

Henri Becquerel and uranium salts – In his laboratory in Paris, Henri Becquerel was fascinated by the apparent connection between X-rays and fluorescent and phosphorescent substances. (Phosphorescent substances, unlike fluorescent ones,

Wavelengths

Radio waves	100,000cm
	10,000
	1000
	100
	10
	1
Light: Infra Red	10^{-1}
UV	10^{-2}
	10^{-3}
	10^{-4}
	10^{-5}
X-rays	10^{-6}
	10^{-7}
	10^{-8}
γ-rays	10^{-9}
	10^{-10}



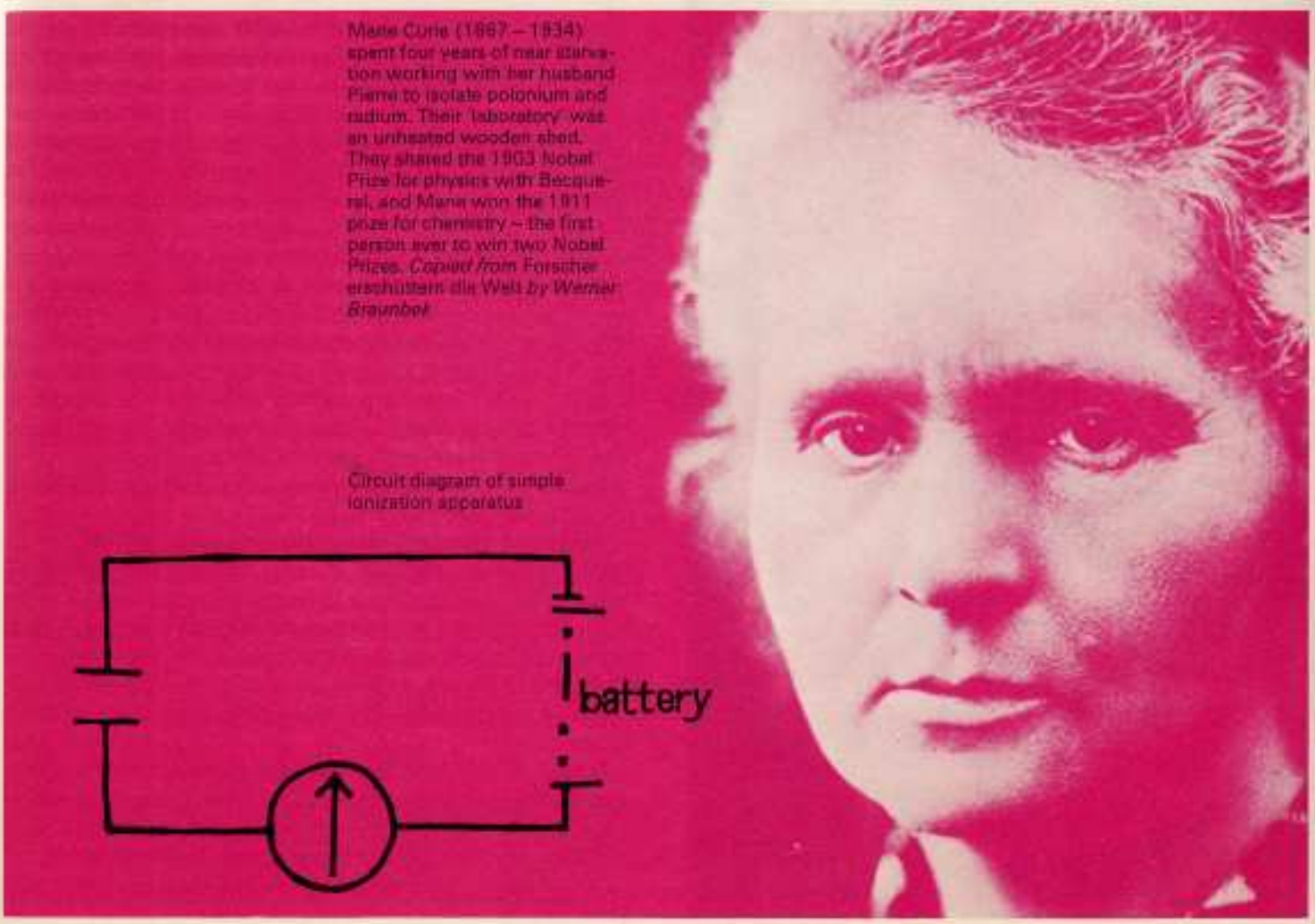
Antoine Henri Becquerel (1852 – 1908) discoverer of radioactivity and joint recipient of the 1903 Nobel Prize for physics. *Copied from* Men and Women behind the Atom *by Sarah Riedman*

continue to glow for some time after the stimulating light source has been removed; 'luminous paint' is an example.) In particular he wanted to find out whether phosphorescent uranium salts, which gave a glow similar in appearance to that of a discharge tube, also emitted X-rays. He put crystals of potassium uranyl sulphate on a photographic plate wrapped in black paper and exposed the whole to sunlight. He found that the plate was blackened in the neighbourhood of the crystals. At first he thought that penetrating rays had been produced together with phosphorescence as a result of exposing the crystal to light; however, one dull day in 1896 he prepared an experiment of this kind but put the crystals and wrapped plate in a drawer. About five days later, he developed the plates and found that the blackening near the crystals was as intense as when he had exposed the crystals to sunlight. He concluded that the radiations were a property of the uranium salt, quite independent of external stimulus; and so, without naming it, he had discovered radioactivity.

Becquerel found that the radiations from uranium penetrated materials, and, like X-rays, could produce shadowgraphs. He is credited with having produced a radiograph of a key by placing it on a wrapped plate and covering it with crystals of a uranium salt. (Both this and the original experiment with uranium crystals are among the easiest experiments in radioactivity, and can be carried out in a school laboratory.)

A further property of the radiations discovered by Becquerel was that they would cause ionization in air and would discharge a gold-leaf electroscope in a similar way to Roentgen's X-rays. (This property of radioactive substances is often used to remove static electrical charges from insulating materials like glass, and quite often a piece of a radioactive mineral is kept in

Marie Curie (1867—1934) spent four years of near starvation working with her husband Pierre to isolate polonium and radium. Their 'laboratory' was an unheated wooden shed. They shared the 1903 Nobel Prize for physics with Becquerel, and Marie won the 1911 prize for chemistry – the first person ever to win two Nobel Prizes. *Copied from* Forscher erschüttern die Welt *by Werner Braunbek*



Circuit diagram of simple ionization apparatus

a sensitive microbalance to avert the weighing errors which charged objects are likely to cause.)

The Curies and radium – Becquerel's young Polish assistant, Marya Sklodowska (later married to Pierre Curie), attempted to measure the ionization with apparatus (see diagram) which is used in various forms today, consisting of two parallel plates insulated from each other and connected through a battery to a galvanometer. When the uranium salt was placed between the plates, the galvanometer indicated a flow of current. She found that all compounds of uranium showed the phenomenon which she named 'radioactivity' and that the more uranium there was, the greater was the effect. It was found that thorium compounds were also radioactive. In the course of her investigations she observed that the uranium ore pitchblende was much more radioactive than uranium and suggested the presence of an element much more active than uranium. In fact several other minerals showed this effect. By carrying out what amounted to a qualitative analytical separation, the Curies found that a highly active substance was precipitated from a solution which contained uranium, and thorium, together with bismuth. They were able to extract the material and show that it had far greater activity than uranium. They claimed it as a new element and suggested the name *polonium* after Marie Curie's native land. Further work showed that a second source of intense radioactivity was associated with barium, and the new element *radium* was claimed.

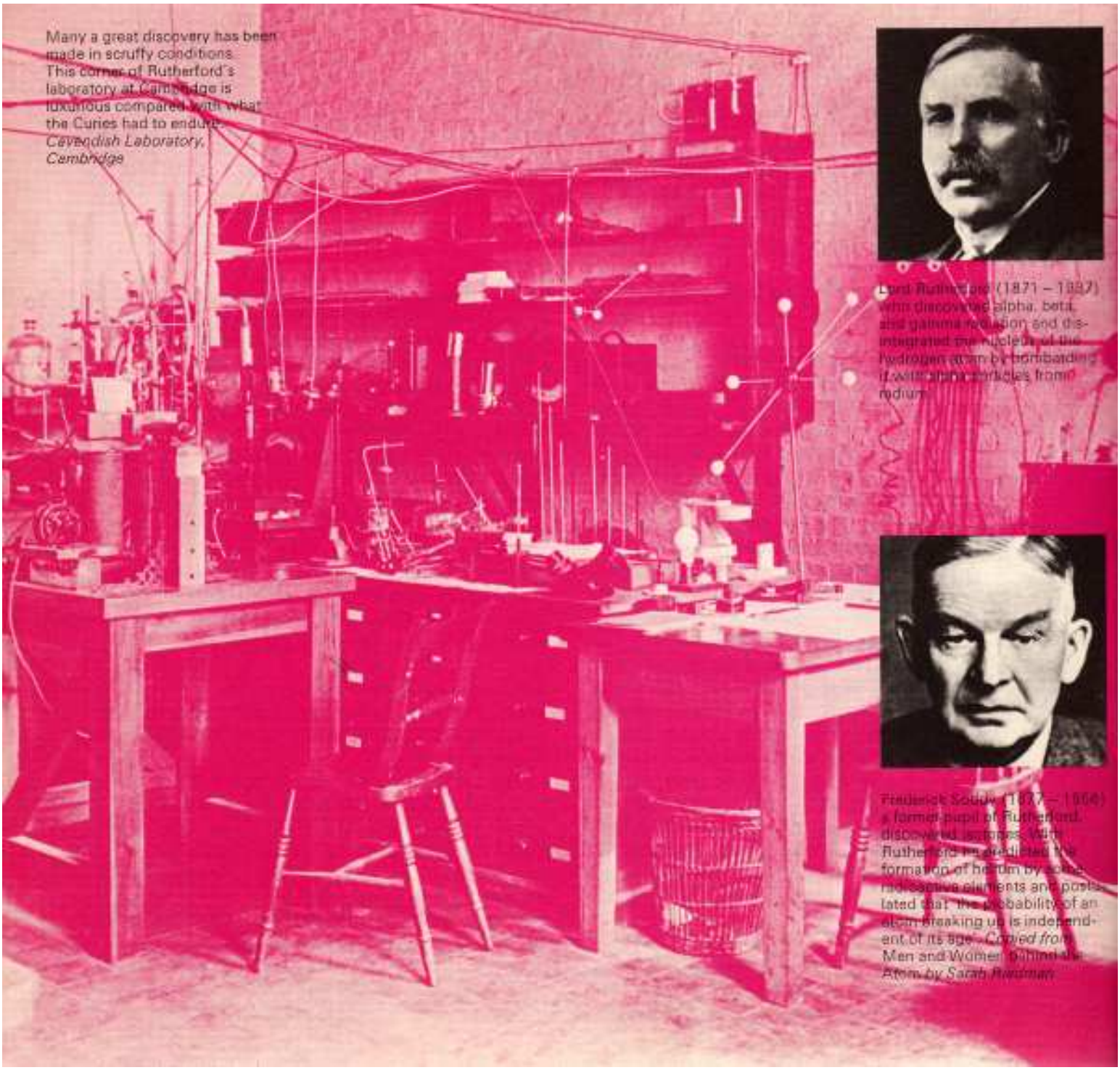
In order to confirm the claim to have discovered two new elements, the Curies set to work to prepare enough of them to produce weighable quantities. This was a tremendous task since they started with a ton of pitchblende residues from which uranium had been extracted. In rather primitive conditions, and turning chemists on a rather large scale, they worked for four years and were able to produce 100 mg of pure radium chloride and to establish the atomic weight of the element.

Work by a number of people established that the radiations from radium had a beneficial effect on certain growths and tumours, so like Roentgen's X-rays, radium was added to the armoury of the medical man, and is still there, although artificial radioactive substances, obtainable in great quantities, have extended the work, to some extent superseding radium.

Early in the new century, the extraction of radium became an industry. The Curies freely gave information about the process of extraction and it is a tribute to their careful work that there has been very little change in the method of extraction since their time. Pierre was killed in a street accident in Paris in 1906, but Marie lived on until 1934.

The radiations from radioactive substances – Marie Curie set out to measure radioactivity but ended with two new radioelements and the start of a new industry. Meanwhile, what of the radiations ?

The Curies observed that radium appeared to make objects near to itself radioactive whereas uranium salts did not behave in this way. Rutherford found that thorium salts behaved as radium did, and gave off a radioactive gas which he called 'emanation'. As the activity of the gas died away the activity of an 'active deposit', left where the gas had been, increased. Rutherford and Soddy explained this by the theory that when an atom of a radioactive element has given out some radiation it becomes the atom of a new element. The new atom might itself be radioactive and it would then throw out another particle and so on. From a number of tests, Rutherford



Many a great discovery has been made in scruffy conditions. This corner of Rutherford's laboratory at Cambridge is luxurious compared with what the Curies had to endure. *Cavendish Laboratory, Cambridge*

Lord Rutherford (1871 – 1937) who discovered alpha, beta, and gamma radiation and disintegrated the nucleus of the hydrogen atom by bombarding it with alpha particles from radium.

Frederick Soddy (1877 – 1956) a former pupil of Rutherford, discovered isotopes. With Rutherford he predicted the formation of helium by series of radioactive elements and postulated that "the probability of an atom breaking up is independent of its age." *Copied from Men and Women Behind the Atom by Sarah Ransman*

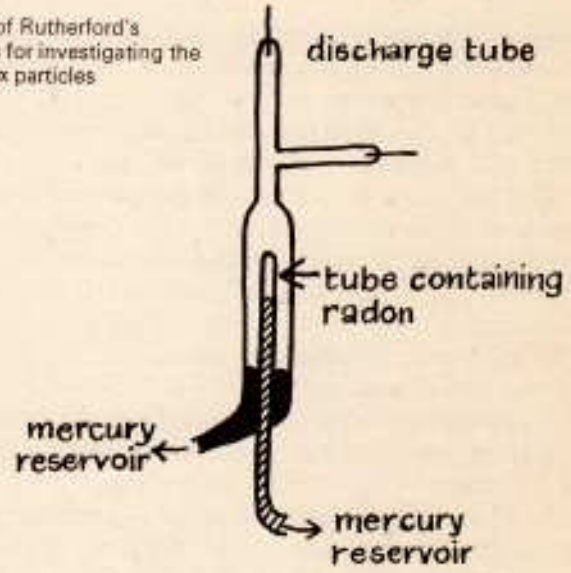
and the Curies recognized that radioactivity contained two different kinds of radiation, which they called alpha (α) and beta (β). Beta rays were found to be deflected by a magnetic field and to have a negative electric charge and to be identical with electrons. Consideration of the amount of bending suggested that the mass of a beta particle was rather more than $\frac{1}{1000}$ that of a hydrogen atom. It took a considerable amount of research to find out the nature of the alpha particle. It could be deflected by a powerful magnetic field but in a direction opposite to that of a beam of electrons. This showed it had a positive charge (opposite to the electron). By considering the force needed to bend a beam of alpha particles in a magnetic and an electric field, Rutherford thought it probable that they were helium atoms which had lost two electrons. He proved this by placing a radioactive gas (radon) in a glass tube, enclosed by another tube which he evacuated (top right). The walls of the inner tube were thin enough to allow the α particles emitted by radon to pass through. After some days, the gas in the outer tube was compressed by mercury into a portion through which an electric discharge could be passed. It showed the spectrum of helium, and this was regarded as definite proof of the nature of the α particle.

A third type of radiation was found to exist. This was not deflected by a magnetic field but had considerable penetrating power. Gamma (γ) rays, as this radiation is now called, were proved after some time to be similar to X-rays but of shorter wavelength. Madame Curie's way of summarizing the electrical properties of the radiations was to suppose that the source of radiations was in a hole in a block of lead so that they would emerge as a narrow vertical pencil. If a magnetic field is applied perpendicular to the paper, the direction of deflection would be as shown in the diagram (bottom right). The heavier α particles are only slightly deflected whereas the light β particles are bent to the left to a greater extent. Gamma rays, having no electric charge, go straight on. It should be pointed out that this is a summary of these properties, and not the result of an experiment. β particles would be bent so much more than α particles that the difference could not be shown in the same experiment.

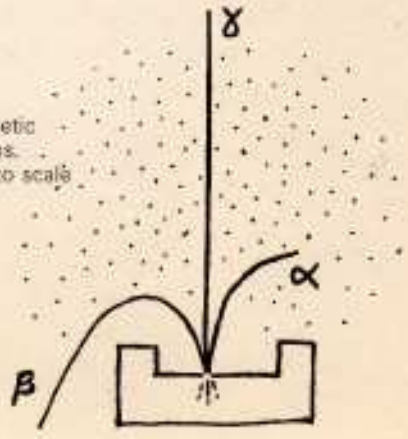
We can summarize the properties of the radiations thus:

	Mass relative to hydrogen	Charge
α	4	+2
β	1/1837	−1
γ	0	0

Diagram of Rutherford's apparatus for investigating the nature of α particles



Effect of a magnetic field on radiations. Deflections not to scale

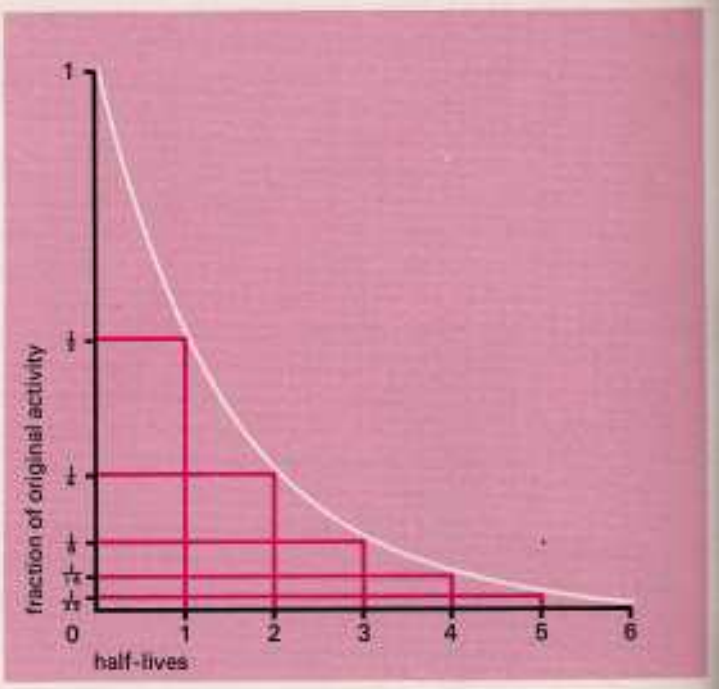


Part 2
Laws of radioactivity

Radioactive decay – The radioactive change of one element into another occurs spontaneously and is not affected by heat, cold, chemical reaction, or any other stimulus. You might think that a piece of radioactive element would decay at a steady rate of so many atoms per second until it was all changed, but this is not so. Experiments have shown that the number of atoms changing is always the same proportion of the total number present. Thus the more atoms of the radioactive element there are present, the more will break up every second, and the more intense will be the radiation thrown out. As the number of unchanged atoms decreases, so the number of atoms breaking up per second will decrease. Each radioactive element has its characteristic fraction of atoms changing at any one moment and this fraction is called the *decay constant* and designated by the Greek letter lambda (λ).

The idea of something growing or diminishing at a rate proportional to its size at any time is fairly easy to understand. Imagine, for example, a child who is given ten shillings and decides to spend it at the rate of half his capital at the end of every week.

Weeks	Money spent		Amount left
	in week	*total*	
0			10*s* 0*d*
1	5*s* 0*d*	5*s* 0*d*	5*s* 0*d*
2	2*s* 6*d*	7*s* 6*d*	2*s* 6*d*
3	1*s* 3*d*	8*s* 9*d*	1*s* 3*d*
4	7½*d*	9*s* 4½*d*	7½*d*
5	3¾*d*	9*s* 8¼*d*	3¾*d*
6	2*d*	9*s* 10*d*	2*d*
7	1*d*	9*s* 11*d*	1*d*
8	½*d*	9*s* 11½*d*	½*d*
9	¼*d*	9*s* 11¾*d*	¼*d*
8			



Notice that the amount left in any week is the same as the rate of spending in that week. If we plot this, we get a curve called an 'exponential'.

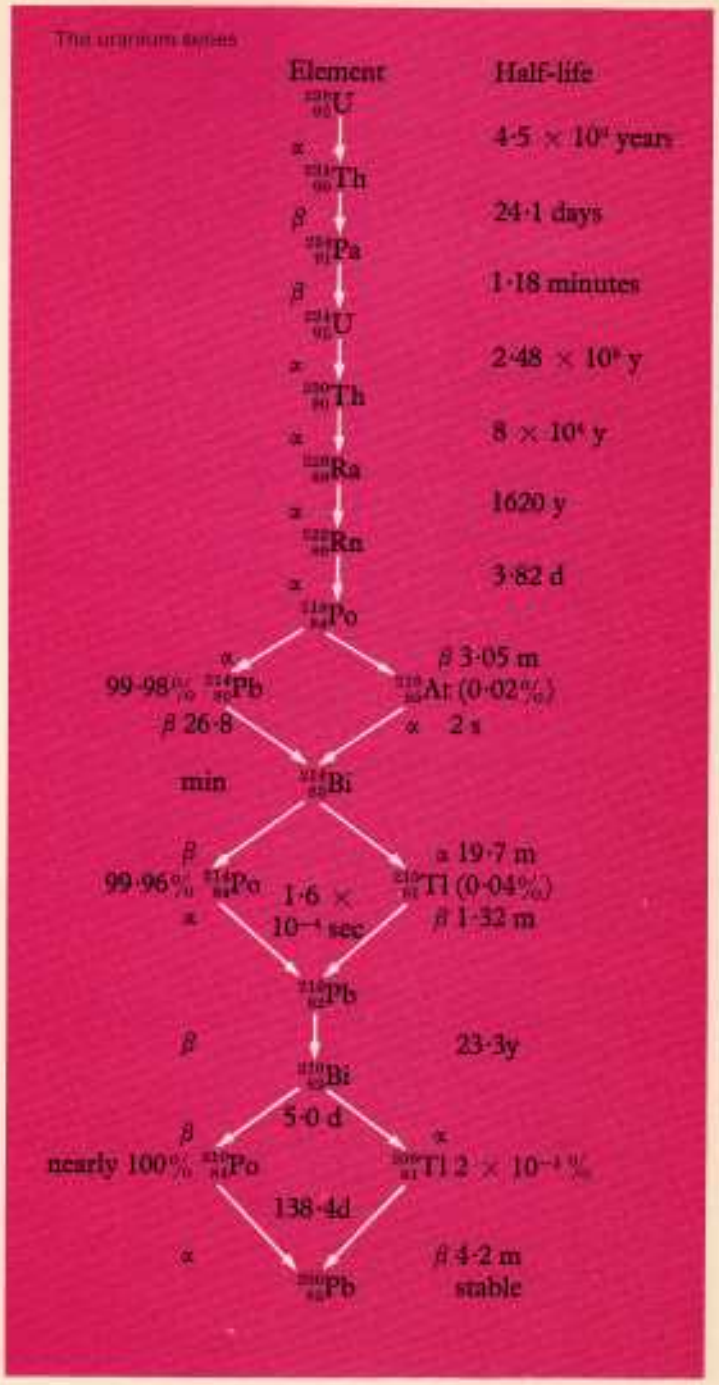
Although the constant, λ, is used in mathematical treatment of complicated problems of decay, another, more informative characteristic of the radioactive element is found convenient for general use. This is the *half-life* of the element – the time it takes for the atoms of the element which are present to be reduced to half their initial number, or (which is the same thing) for the radiation given out to be reduced to half its

original intensity. It is written $t_{\frac{1}{2}}$. Half-lives range from exceedingly small fractions of a second (such as 10^{-21} seconds for ^{5}He) to thousands of millions of years e.g. $1{\cdot}3 \times 10^{9}$ years for ^{40}K. The half-life of a substance is a fundamental property and is unaffected by chemical and physical agencies.

If we started with a million radioactive atoms, some would decay quite independently of the others, and there would be a time when only half a million were left. This time would be the half-life. After another half-life, a quarter of a million radioactive atoms would be left, and so on. If we plot this we get an exponential curve (see diagram). After n intervals, $(\frac{1}{2})^n$ of the original number is left. Thus after ten half-lives $\frac{1}{1024}$ million, or about 1000 radioactive atoms are left, and after another ten half-lives, one radioactive atom (in theory, at any rate, although one cannot put a physical reality to this mathematical idea, since the next stage would involve a fraction of an atom).

A simple illustration of half-life is to suppose a large audience listening to a boring speaker. Occasionally people in the audience will fall asleep, quite independently of each other. A measure of the dullness of the speaker might be found by seeing how long it took for half the audience to fall asleep! Speakers could then be graded with 'half-lives'.

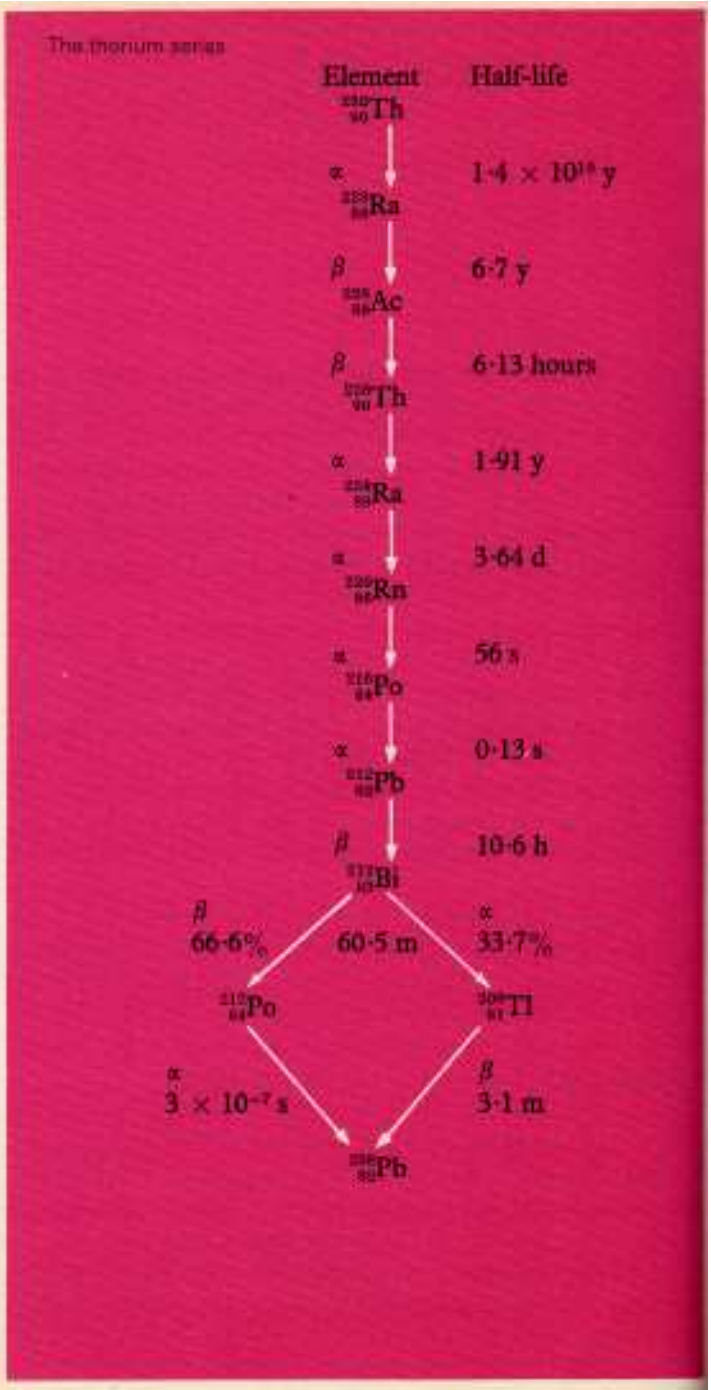
Parent and daughter activities and radioactive equilibrium – Some radioactive substances decay into others which are themselves radioactive. In a few cases this process continues in a radioactive series involving many stages, and only ending when a non-radioactive (or 'stable') element is produced. For instance, one form of uranium found in nature is ^{238}U (uranium with an atomic mass of 238) which has a half-life of 4,500,000,000 years, and emits an α particle when it decays.



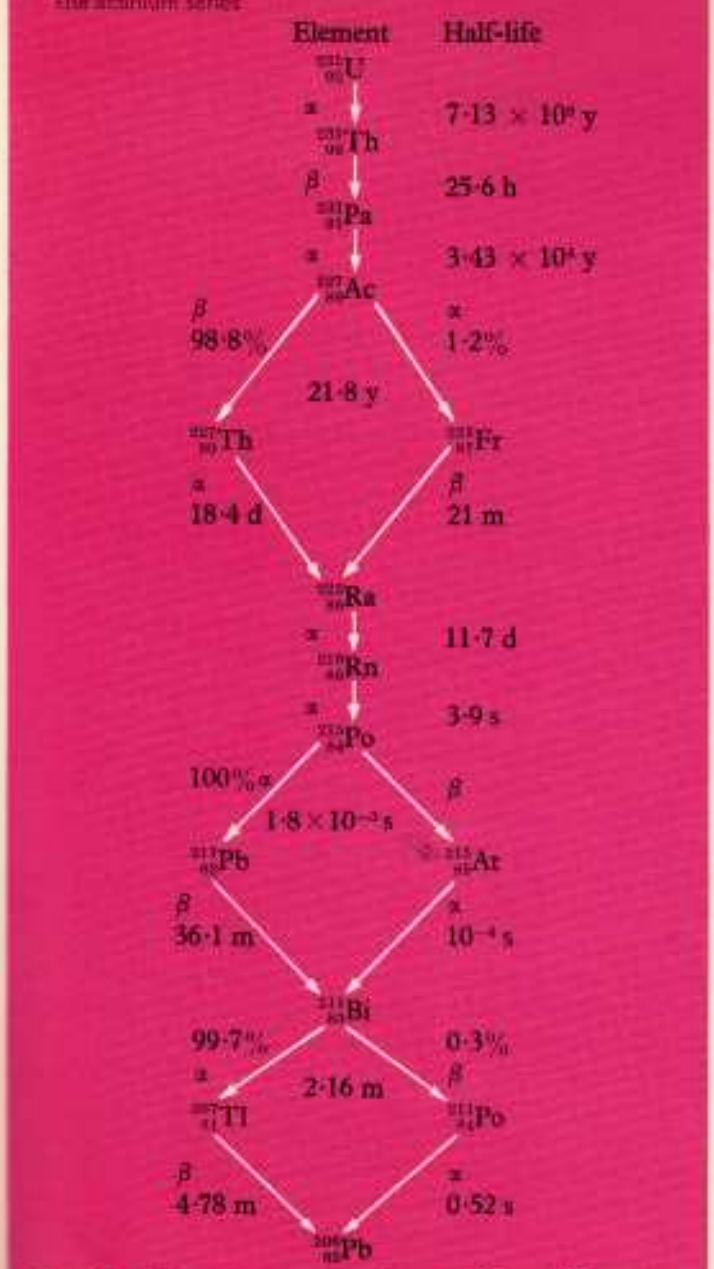
If an atom does this it changes to an atom of thorium of atomic mass 234, which has a half-life of 24·1 days. This in turn may decay and produce a new atom by emitting a β particle, becoming protactinium of mass 234 and half-life 72 seconds, and so through further stages until atoms of lead of mass 206 become the final product of the series. One can say that ^{238}U is the parent, and ^{234}Th the daughter, which in turn becomes the parent of ^{234}Pa, and so on.

In nature there are three series of this kind, two starting from uranium, and one from thorium. A fourth consists of artificially produced elements. The four series are shown on pages 9, 10, and 11. In each case the lefthand column shows the changes from one radioactive material to another, and sometimes shows alternative ways of changing, either an α particle followed by β, or the reverse order. Some aspects of these figures will be clearer on second reading when the concepts of isotopes and of the changes following the emission of α and β particles have been assimilated.

Equalibrium – The uranium series (page 9) shows that atoms of ^{234}Th owe their existence to the decay of atoms of ^{238}U and, in turn, atoms of ^{234}Pa only exist because atoms of ^{234}Th decayed. All the time ^{238}U atoms are present, the series goes on, and the radioactive daughters which are produced go on producing daughters in turn as they decay. In time the whole series settles down to what is called 'radioactive equilibrium', that is, the number of atoms each daughter element is getting from its parent and the number it is losing to its own daughter are the same, so that the amount present of each daughter element remains steady. Thus when a uranium series is in equilibrium the only elements which change in quantity are the uranium at the top (^{238}U), which decreases, and the lead



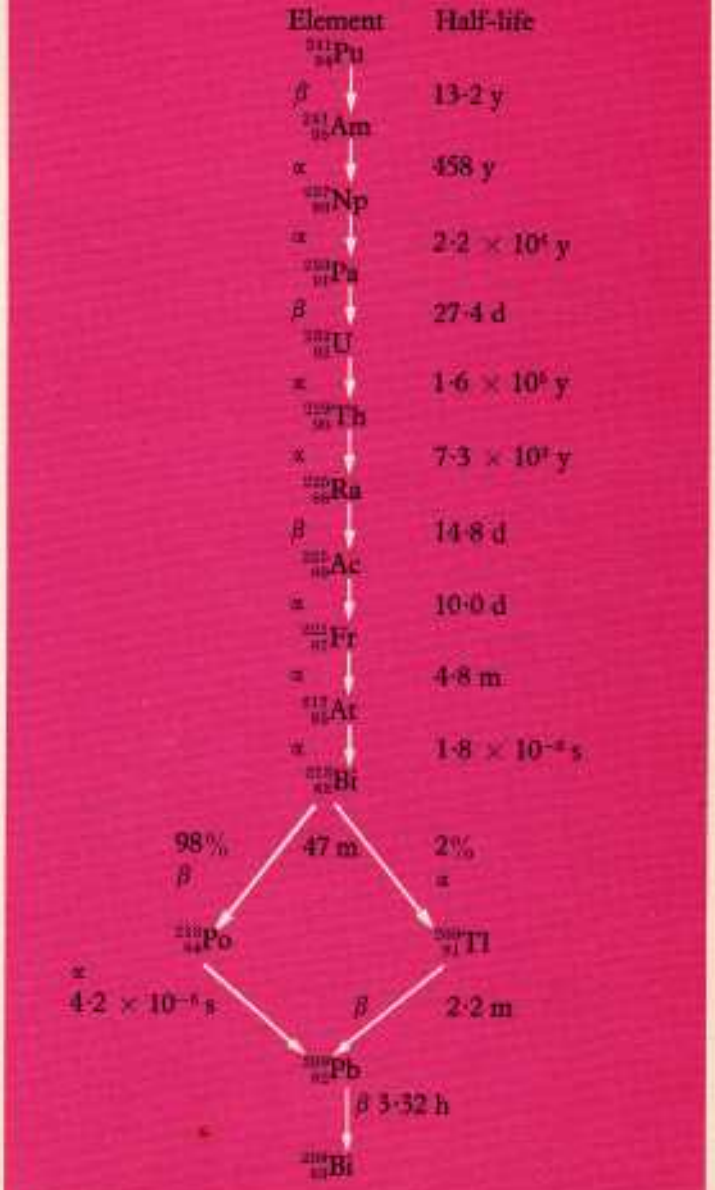
The actinium series

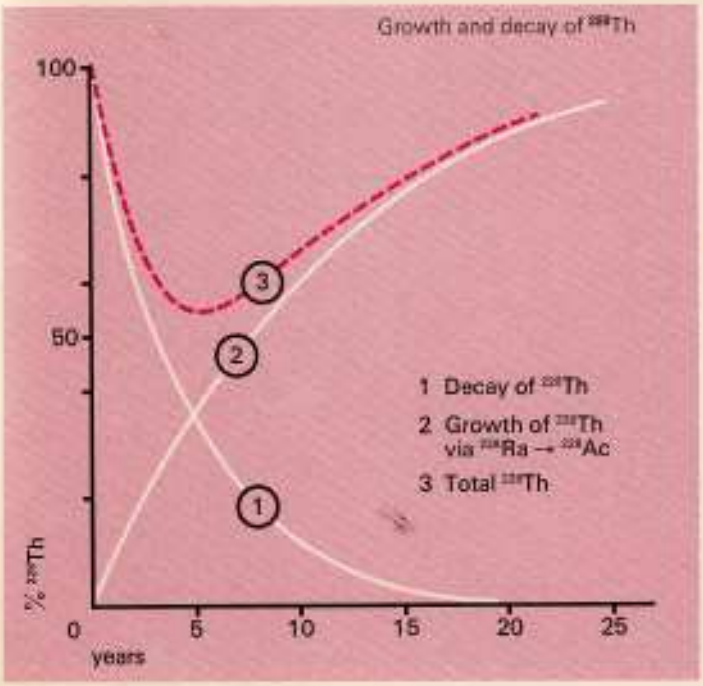


Note that this series contains elements 85 and 87, astatine and francium, as does the neptunium series.

The neptunium series

This series has been produced artificially, although very small amounts of ^{237}Np have been found in uranium minerals.





at the bottom (^{206}Pb), which increases. If the half-life is 24 days, equilibrium will be half way to completion in 24 days, $\frac{3}{4}$ in 48, $\frac{7}{8}$ in 72, and as near as no matter complete in 120 days. If we look down the uranium series it is clear that only in geological time will the whole series be in equilibrium since ^{234}U has a half-life of $2{\cdot}48 \times 10^5$ years, and the next stage would not be in equilibrium until over 1 million years.

It is possible to show the decay of a daughter product and its growth from the parent by a simple experiment such as the one described in Topic 24 of the Sample Scheme in the Nuffield Chemistry Course (Experiment 24.2c).

There are interesting examples of equilibrium in the thorium series (page 10). ^{228}Ra (mesothorium), half-life 6·7 years, is often removed from thorium ores for use in luminous paint. Further down the series there is ^{228}Th with half-life of 1·91 years, whose atoms decay, but are replaced as ^{228}Ra decays. The radium in turn owes its existence to the decay of ^{232}Th. As in the uranium series, equilibrium is re-established, but it takes about 35 years to get back to the state before the ^{228}Ra was removed. If we plot a curve of ^{228}Th decaying, and also of the growth of ^{228}Th from ^{228}Ra, and then make a 'sum curve' of total ^{228}Th at any time (see graph left), it is clear that this goes down to a minimum at about five years and then starts to grow. Apart from being an interesting example of growth and decay, there is the practical point that if thorium salts which are not in equilibrium are used as sources of ^{212}Pb and ^{212}Bi, the activity produced depends upon the 'age' of the thorium salt.

Part 3
What causes radioactivity?

Isotopes – We have seen that in a radioactive series the same element may appear more than once. For example, in the uranium series polonium appears with an atomic mass of 218, 214, and 210. The fact that elements may have different atomic masses was noticed by F. W. Aston in 1919 with the aid of a mass spectrometer, an instrument in which a beam of electrically charged atoms is acted upon by an electric and magnetic field and separated into atoms of different atomic masses. He found that neon of atomic mass 20·2 consisted of two types of atom of masses 20 and 22. Even before this, Frederick Soddy had suggested that elements might consist of groups of non-separable atoms of different atomic mass, occupying the same place in the periodic table. He coined the name *isotope* for these atoms, from the Greek words meaning 'same place'. By no chemical means was it possible to separate the two forms of the element since they are chemically identical.

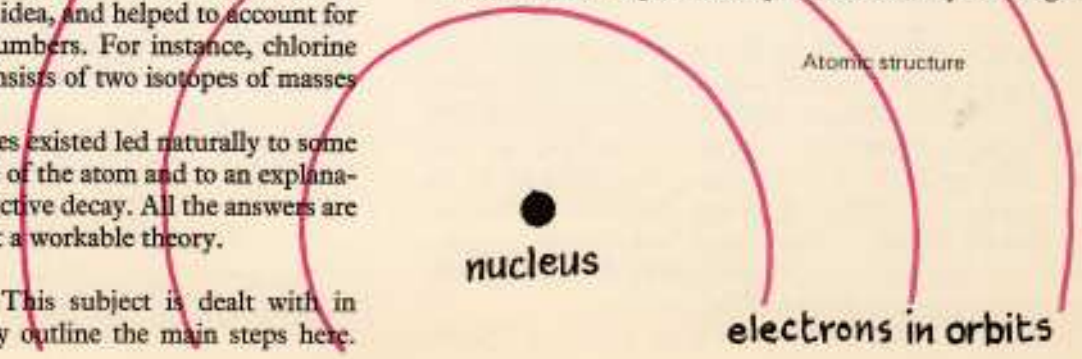
It had been noticed already that not many of the elements had atomic masses which could be expressed as whole numbers. This made it difficult to regard their atoms as being made up as multiples of simple building blocks. The concept that an element consisted of a mixture of atoms of different atomic masses fitted in well with this idea, and helped to account for the differences from whole numbers. For instance, chlorine whose atomic mass is 35·5 consists of two isotopes of masses 35 and 37 in the ratio 3:1.

The recognition that isotopes existed led naturally to some rethinking about the structure of the atom and to an explanation of what happens in radioactive decay. All the answers are not known yet, but we can get a workable theory.

The structure of the atom – This subject is dealt with in *Inside the Atom*; we will only outline the main steps here.

In order to find out what the atom was like, Rutherford and others observed what happened when radiations bombarded sheets of thin metal foil. This approach was rather like coming to a high walled town which couldn't be penetrated or looked into from above, and trying to throw something over the wall. A stone might betray whether there were a roof, for one thing. If the stone were thrown back, however, there would evidently be someone the other side. If other objects came back – empty bottles, pop music discs, or the like – we might get some idea about the people inside! Rutherford bombarded gold foil with α particles and found that although most of them passed through, some were deflected. The simile he used later in discussing this was, 'It's as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you'. From consideration of this scattering, Rutherford concluded that the atom had a central core or nucleus which represented nearly all the mass but was only some $\frac{1}{100,000}$ of the size of the atom. That is, the atom is nearly all space. Later Niels Bohr and Rutherford suggested a model of the atom having a positively charged nucleus and electrons going round in orbits.

This did not explain isotopes satisfactorily although the



Disintegration of a nitrogen nucleus by an alpha particle. *A.E.R.E. Harwell*

existence of an uncharged particle in the nucleus was suspected. In 1932 Chadwick discovered an uncharged particle and named it the neutron, and a new workable theory emerged. The nucleus is supposed to contain protons with a positive charge, and neutrons with no charge, each having about the same weight. The number of protons determines the charge and hence the nature of the element, and in a neutral atom there is an equal number of electrons with negative charges, balancing the positive charges of the protons.

The number of neutrons present in the nucleus is definite, but is variable within limits. For instance, carbon has 6 protons and 6 electrons but it can have 4, 5, 6, 7, or 8 neutrons. The atomic mass is the sum of the protons and the neutrons, so the atoms have different atomic masses, ranging from 10 to 14. But since there are always 6 protons, they are all atoms of carbon, and are isotopes of carbon. The atomic mass normally associated with carbon is 12; in fact atomic masses are now based on the mass of ^{12}C being 12·0000. ^{13}C is known in nature, and is present to the extent of 1·1 per cent in ordinary carbon. The other isotopes are artificial. The first two have insufficient neutrons for stability, whereas the last one, ^{14}C, has one neutron too many. These 'unstable' isotopes are called *radioisotopes*.

If there is a neutron too many, there is a chance that a neutron will change into a proton if that would give a more stable nucleus with less energy associated with it. The change is accompanied by the emission of an electron which leaves at high speed (a β particle). There may be further release of energy as γ radiation.

A way of picturing conditions in an atom is to suppose the neutrons and protons to occupy various levels representing different amounts of energy; the higher up, the greater the energy.

If a change can take place to give less energy in the atom it will take place, and energy will be given out.

In ^{14}C, there would be less energy if one neutron moved to the highest proton level. In a large population of atoms, individual atoms will change at random (as, for instance, a large number of soap bubbles released at the same time will all eventually burst, but individual ones burst early or late quite independently of the fate of others in the group). It is not possible to predict when any one atom will change, but if there is a large number, it is possible to find by experiment, and to some extent by theory, a measure of the probability of an atom breaking up in a given time (the decay constant) or to express the stability in terms of half-life, as previously discussed. Generally if there is a large amount of energy to be lost, the half-life is short, and vice versa, but this is only an approximate guide.

If in ^{14}C a neutron changes to a proton, the mass remains almost, but not quite, the same. The small change in mass is explained by Einstein's equation $E = mc^2$, where E is energy, m is mass, and c is the velocity of light, all measured in

appropriate and matching units. This means that if mass is destroyed, energy appears. A particle at rest has one mass, but if it is moving fast, its relative mass is increased because of its energy of motion. A proton has less mass than a neutron, so the change is accompanied by a release of energy. Since in the decay of ^{14}C a neutral particle changes to a charged one, the atomic number (the number of protons) goes from 6 to 7. That means that the atom changes to one of nitrogen (the half-life of ^{14}C is 5770 years, so that if we had a gram of ^{14}C – about 5×10^{22} atoms – it would take 5770 years to make half a gram of nitrogen).

We often write these nuclear transformations as equations, showing changes of mass and charge. Carbon of atom mass 14 is written $^{14}_{6}C$, the top left figure being the mass, and the bottom left being the positive charge, or the atomic number, or the number of protons (which amounts to the same thing). Some people prefer to write it as $_{6}C^{14}$, but there are sound scientific reasons for keeping all the nuclear physics to the left, leaving the right for ionic charge or the number of atoms in the molecule, e.g. $^{2}_{1}H_{2}^{+}$ is a heavy hydrogen molecular ion, $^{35}_{17}Cl^{-}$ is a chloride ion, and so on.

For the disintegration of ^{14}C, the equation is:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \text{energy}.$$

$^{0}_{-1}e$ signifies an electron, and when it is regarded as a particle emitted during the change, it is called a β particle.

^{11}C has only 5 neutrons and 6 protons. To achieve a stable nucleus, a proton has to change to a neutron. This means a loss of positive charge, and a change to the element next below carbon in the Periodic Table – boron. What is emitted has to have negligible mass but a positive charge, and it is termed a 'positron', and this is created out of energy, provided there is more than a certain minimum amount available for this purpose. (Some neutron deficient nuclei become stable by a change from proton to neutron followed by capturing an electron from an orbit close to the nucleus.) The equation for the decay of ^{11}C is:

$$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}e + \text{energy}.$$

The emitted particle is written β^{+}. The half life of ^{11}C is 21 minutes.

It must be pointed out that this treatment of the structure of the atom and the way a nucleus changes, is a simplified one, which leaves some questions unanswered, and only partly answers others. For instance, if the nucleus contains only positive charged particles, one might expect them to repel each other. There are many theories about the forces within the nucleus, and about the nature of the particles. Some fifty sub-nuclear particles have been named, and there are theories about how they take part in the structure of the nucleus. Much light was shed on the matter by work published in 1964 which suggested family relationships between the particles, but the last word has not been written on this matter by a long way. For the purpose of studying the uses of radiations and the properties of radioactive materials, the Rutherford-Bohr atom gives a workable model.

The energy of the radiations – When a radioactive substance emits radiations, α, β, or γ, it does so because it has an excess of energy. Most of this energy is given to the particle or radiation which is emitted. We are familiar with the association of energy with radiations of various kinds, e.g. heat radiated from a hot body conveys heat to a body absorbing the radiations. When X-rays are produced in an X-ray tube by directing an electron beam accelerated by a voltage on to a metal electrode, the energy of the X-rays is related to the voltage. A unit of use in discussing nuclear and atomic energies is the electron volt – the energy represented by an electron moving through a potential difference of 1 volt. A 100,000 volt X-ray machine may give X-rays of energy approaching 100 KeV. The forces between atoms in a molecule are a few electron volts (eV). The binding energy of electrons close to the nucleus is some thousands of electron volts (KeV). Energy changes in the nucleus are greater and may be millions of electron volts (MeV). These units may be connected with other units of energy, e.g. 1 MeV $= 1{\cdot}6 \times 10^{-6}$ ergs. A homely comparison is that 1 MeV is the energy needed to lift a fly $\frac{1}{100,000}$ inch!

The energy associated with radiations from a radioactive substance is characteristic of that substance and, like the half-life, can be measured to help identify the radioactive substance. For instance, radioactive phosphorus of mass 32 has a half-life of 14·3 days and gives out radiation of maximum energy 1·71 MeV. ^{238}U gives out α radiation of energy 4·19 MeV and has a half-life of $4{\cdot}51 \times 10^{9}$ years.

Part 4 Radioactive substances, natural and man-made

Natural radioelements – Some of these have existed for thousands of millions of years and form series comprising decaying parents with active daughters. As well as this there are a few long-lived isotopes of certain elements which had an unstable mixture of protons and neutrons when they were made and have a very long half-life. An example is ^{40}K which is present to the extent of 0·011 per cent in all potassium and has a half-life of $1{\cdot}3 \times 10^9$ years. This does not amount to much radioactivity, since it gives 28 beta particles per second per gram of ordinary potassium.

A few neutrons are produced in nature, mainly by highly energetic radiation (cosmic rays) hitting atoms in the upper atmosphere, but to some extent by the breakdown of very heavy elements like uranium. One interesting result of having neutrons produced in the upper atmosphere is that they react with nitrogen and produce radioactive carbon. The equation goes like this:

$$^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{14}_{6}C + {}^{1}_{1}p$$

nitrogen + neutron ⟶ carbon + proton.

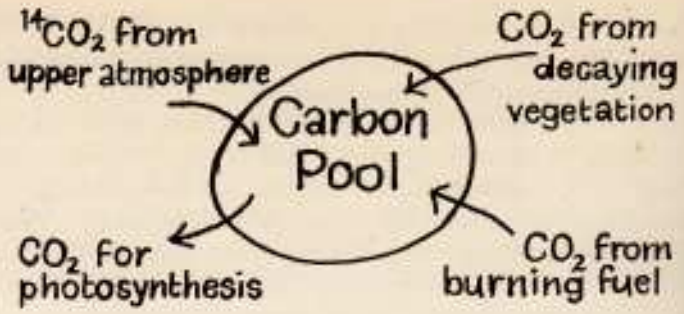
As you see, both the masses and the charges balance. The spare proton picks up a free electron and becomes a hydrogen atom.

Another equation is:

$$^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{12}_{6}C + {}^{3}_{1}H$$

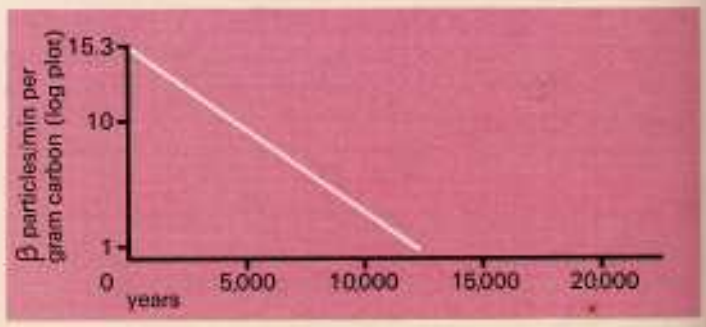
nitrogen + neutron ⟶ carbon + tritium.

Hence two radioactive gases are formed in the atmosphere (the carbon occurs as $^{14}CO_2$). Probably the more interesting one is ^{14}C because its presence means that every living thing containing carbon also contains radioactive carbon, because all the carbon in photosynthesis comes from atmospheric CO_2.



There is a 'pool' of CO_2 into which $^{14}CO_2$ from the atmosphere and CO_2 from animal and vegetable sources go. There is a balance of radioactivity which results in 15·3 beta particles per minute per gram of carbon (natural potassium gives out 28 per second or 1680 per minute). Thus there is a balance of CO_2 in nature although man-made events upset it. CO_2 from coal contains no ^{14}C because it has practically all decayed away, so near industrial towns the ^{14}C content is a little below average. When nuclear bombs are tested there is a release of neutrons which temporarily increases the ^{14}C content by a little.

Radio carbon dating – Suppose a carboniferous object is preserved; for example, a piece of wood or a scroll may be buried and kept away from the normal processes which would cause it to rot and so give back CO_2 to the pool. Then the radio carbon in it which has a half-life of 5770 years, will have less activity per gram than fresh carbon has. If we can find out how much radio carbon there is per gram, it is possible to say how old the object is, right back to 20,000 or, according to some, 30–40,000 years.



As you see, we haven't much activity to start with, but after 20,000 years there is less than 1 beta particle per minute per gram. With a great deal of care and special apparatus, it is possible to measure at these low levels of activity, and objects dated by the radio carbon method have been checked by other evidence. One difficulty is that activity in the air, in the soil, and in material used to make the apparatus and shield it may be more than we are measuring. The cosmic radiation makes a contribution too and it is necessary to take very special precautions to reduce the effect of this 'background'.

Here are a few results obtained:

Charcoal from Stonehenge	3800 ± 275 years
Cypress beam from a tomb – thought to be 4500–4650 years old	4800 ± 200
Wheat and barley grain from an Egyptian tomb	6390 ± 180
Peat of Neolithic age	6050 ± 380

The righthand figures (±275 for instance) show that the activity cannot be precisely determined since statistical variations apply.

How do we get radioelements?

1. Extraction of daughter products – We have already seen that natural uranium decays from ^{238}U to ^{234}Th and that the series continues down to ^{206}Pb. In nature this series is in equilibrium, that is to say, all the elements are being produced and decay and they all depend for their existence on the supply of parent elements which come from the decay of uranium.

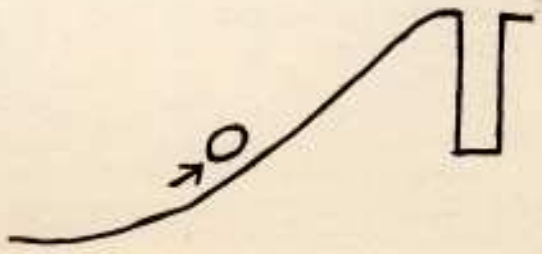
$$^{238}U \xrightarrow{\alpha} {}^{234}Th \xrightarrow{\beta} {}^{234}Pa \xrightarrow{\beta} {}^{234}U \xrightarrow{\alpha} {}^{230}Th \xrightarrow{\alpha} {}^{226}Ra$$

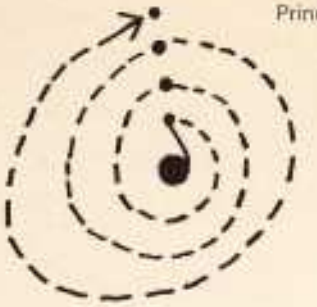
We have already mentioned Experiment 24.2c of the Nuffield Sample Scheme, in which protactinium is separated from uranium nitrate by solvent extraction using amyl acetate. There are other methods of carrying out the separation such as using ion exchange resins, but the solvent extraction method has the merit of simplicity.

The thorium series has some useful daughter products. A gas thoron (an isotope of radon) is given off and one of its decay products, ^{212}Pb, can be electrodeposited on to aluminium. ^{212}Pb decays to ^{212}Bi and these can be separated. This is a good illustration of the fact that in beta decay there is a change of element to one of higher atomic number. Another daughter product of thorium is ^{208}Tl. This has a half-life of 3 minutes and is removed from a thorium solution by passing it through ammonium phosphomolybdate. Everything goes through except the thallium.

2. Irradiation – A stable nucleus can be bombarded with particles to produce a radioactive isotope. If they are charged particles, such as protons or alpha particles, they will be repelled. In order to penetrate the nucleus this force has to be overcome (it's rather like trying to get a ball into a hole at the top of a hill).

In order to acquire this energy the particle is accelerated





Principle of the cyclotron

Synchro-cyclotron at Harwell, a machine that accelerates protons to very high speeds in a spiral path. The particles are kept in the spiral by a magnetic field and are accelerated twice in each revolution by an electric field, produced by a radio-frequency oscillator.
U.K. Atomic Energy Authority

by means of a high voltage. There are various methods, such as the cyclotron, which works by giving the particle a kick each time it goes round an expanding circular path. If we consider a ball on the end of a string which is wrapped round a pole, and we hit it with a tennis racket to unwind it, and arrange to hit it again at every revolution, we might time our hits so that it takes the same time for each revolution in spite of its longer path. A cyclotron is a large device which includes powerful electromagnets often twenty or more feet in diameter, to cause the particle to go round in a spiral, while an accelerating voltage is applied at each revolution. The particles used are usually protons, deuterons (the nuclei of heavy hydrogen having one proton and one neutron), or α particles, and they circulate in a flat evacuated tank which fits between the magnets. The charged particles are produced in the centre of the system, and the material to be bombarded is placed at the outer end of the spiral. It is generally metallic, and has to be cooled, since the bombardment produces heat which could cause the target to volatilize. In some cyclotrons the beam of particles can be deflected out of the spiral and used to bombard liquid or gaseous material, or to produce a beam of neutrons by hitting beryllium in suitable circumstances. Chemical separation has to be carried out to remove the radioisotope from the target material.

If magnesium is bombarded with deuterons, ^{22}Na is produced according to the equation:

$$^{24}_{12}\mathrm{Mg} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{22}_{11}\mathrm{Na} + {}^{4}_{2}\mathrm{He}.$$

The second item on the righthand side is one way of expressing the fact that an α particle is produced: the equation is sometimes shortened to ^{24}Mg (d, α) ^{22}Na. ^{22}Na is a neutron-deficient isotope with a half-life of 2·6 years.

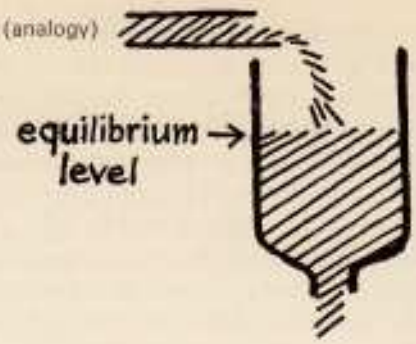
Cyclotron-produced radioisotopes are expensive to produce because only one target can usually be bombarded at a time, and the number of particles which hit it depends (among other things) on the intensity of the beam and the time of bombardment, and a cyclotron costs a lot to run.

Suppose we bombarded the nucleus with a particle which had no charge. In this case the simile is that one is trying to get a golf ball to go into a hole on a flat green. There would be no force to overcome, and the particle would only have to get itself to the right place to be captured. A neutron is an

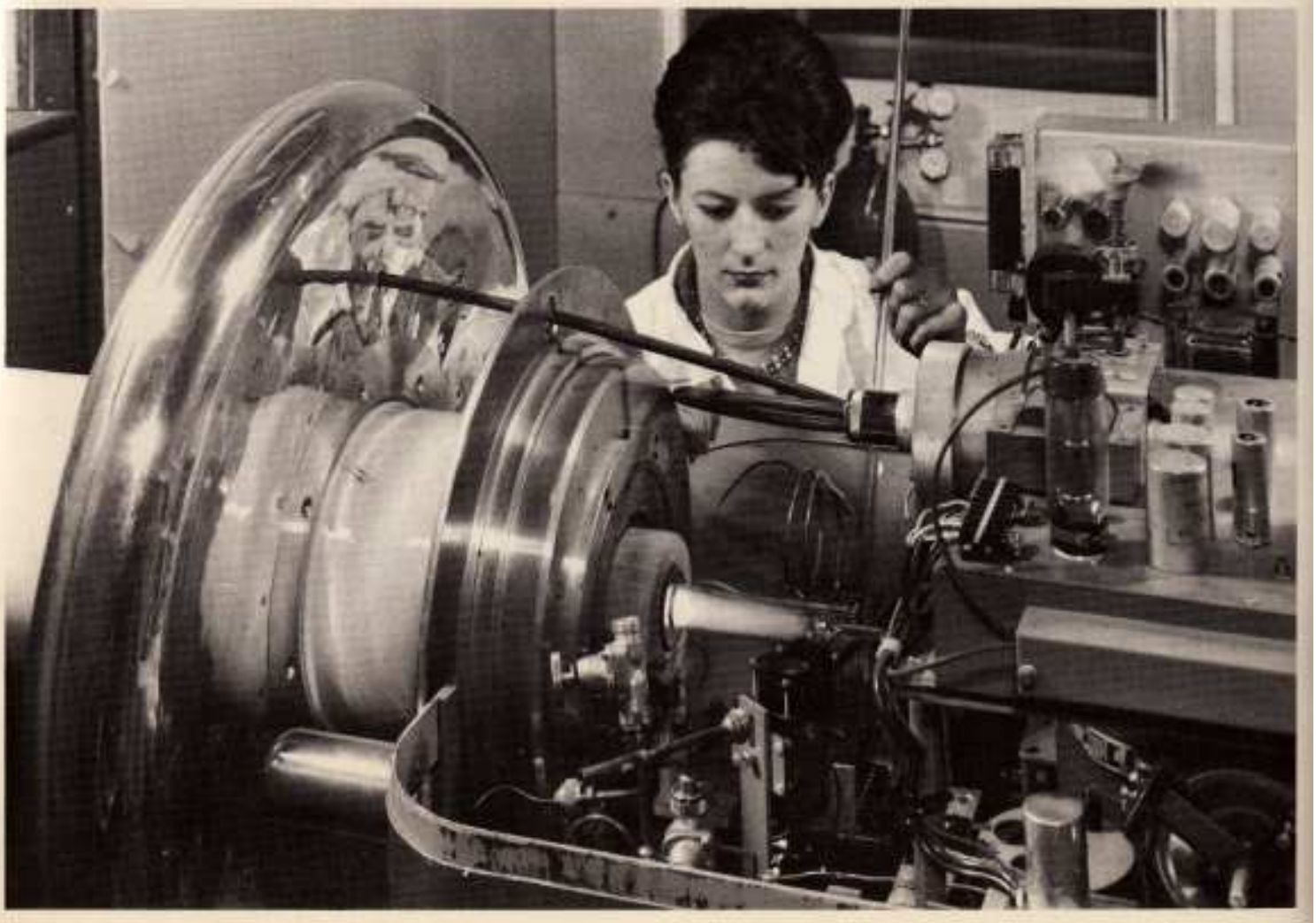
uncharged particle, so it can be accepted by another atom. If we return to the analogy of the golf ball, we see that it has to be going slowly or it may leap over the hole. In the same way, a neutron has to be going slowly in order to be captured. In a reactor there are rods of uranium separated by blocks of graphite, by 'heavy water' (deuterium instead of hydrogen), or in some cases, by ordinary water. The spacing, and the arrangement of the graphite are such that a neutron, which is occasionally given out by a mass of uranium and leaves at high speed, hits nuclei of graphite or hydrogen, and bounces off, slowing down at each bounce. It is arranged that the neutron is going slowly enough, when it reaches the next uranium rod, to be captured. When this happens, there is a probability that an atom of uranium will break into two parts (nuclear fission), and in this process, two or three more neutrons are produced. These go on through the 'moderator', as it is called, are slowed down, and cause more fissions. All this happens at high speed, and a 'hailstorm' of neutrons is produced in a short time. In the Harwell reactor 'BEPO' about 10^{12} neutrons pass through one square centimetre per second at its centre, where

The gas cooled, graphite moderated reactor at Windscale which uses uranium oxide enriched with ^{235}U as fuel.
U.K. Atomic Energy Authority

Build-up of activity (analogy)



A scientist at Windscale inspecting a neutron accelerator which produces neutrons by bombardment of a tritium target with deuterons. *U.K. Atomic Energy Authority*



the 'neutron flux' is at its maximum. It is possible to arrange that many targets are bombarded at the same time, and with so many neutrons about, it is possible to transform a large number of atoms. Thus, if a gram of gold is bombarded in the centre of 'BEPO' for a day, over a curie of radioactive gold is produced.

It is rather like injecting a 'disturbing influence' into a group. If he is absorbed, the energy he gives the group may lead to a great deal of activity and the whole nature of the group may be changed. There may even be an expulsion of another member and a continued output of energy! With atoms there may be a disturbed state, which leads to some radioactive forms which in turn give out energy. All atoms are not equally likely to be modified, and there are physical properties which make it possible to calculate how much activity will be produced. For instance, a reactor may produce 10^{15} neutrons per second, but a laboratory source may only produce a few thousand each second. Other things being equal, the reactor will produce curies of activity while the laboratory source only makes very small fractions of a microcurie (1 millionth of a curie).

In every case there is a balance between what is produced and what decays. Imagine pouring water steadily into a long cylinder with a small hole in the bottom. If we carry on we will arrive at a point when the increase in pressure due to the height of the water in the cylinder makes the rate of outflow the same as the rate of inflow. If we pour water in faster, the height will rise to a new steady level (see left).

The analogy is a rough one, but one can imagine a supply of radioactive atoms being produced at a constant rate and decaying. Given time the activity reaches an equilibrium value. In one half-life it reaches half this value, in two half-lives, three-quarters, in three, seven-eighths, and so on. The activity produced (5) depends upon:

1. The number of bombarding particles per square centimetre per second (ϕ).

2. The probability of hitting the target and bringing about the reaction. This is called the 'cross-section' (σ) and is expressed in units of target area called 'barns' (1 barn $= 10^{-24}$cm^2).

3. The number of atoms available to be hit. This depends upon the weight and the atomic mass (A).

4. A 'build-up' factor depending upon the length of the bombardment in terms of half-lives ($t/t_{\frac{1}{2}}$).

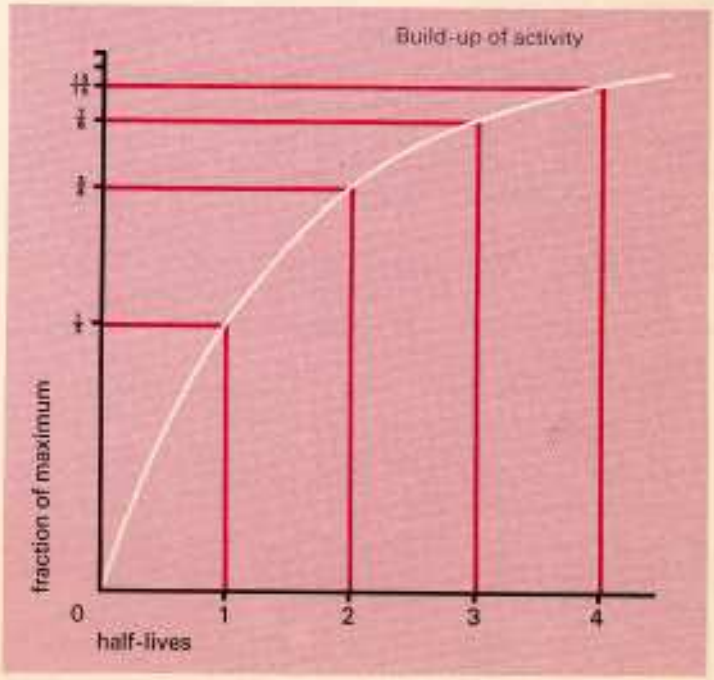
Here is the formula:

$$S = \frac{0{\cdot}6\ \phi\ \sigma}{3{\cdot}7 \times 10^{10} A}\ (1 - (\tfrac{1}{2})^{t/t_{\frac{1}{2}}}) \text{ curies per gram.}$$

(The 0·6 comes from Avogadro's number and a little rearranging of the size of units.)

For gold, σ is 96, so if ϕ is 10^{13} we can make about 8 curies of radioactive gold per gram (1 gram of radium is about 1 curie of activity).

Artificial radioisotopes – Before the 1939–1945 War virtually the only radioactive material in use was a few kilograms of radium used in hospitals. Now many millions of curies of activity have been produced artificially, and one source used commercially may be equivalent to about 300 kilograms of radium. Although there are only 90 natural elements, there are over 700 artificial radioactive isotopes. This means that each



element may have a number of radioactive isotopes, some produced by bombardment of its own stable isotopes and others by different bombarding processes. Some of the radioactive products have such short half-lives that there is scarcely time to measure them by decay and special methods are necessary. Sodium has only one stable isotope. If we add a neutron to it we get ^{24}Na with a half-life of 15 hours. If we bombard magnesium with neutrons we get some ^{24}Na and a little ^{28}Na and ^{26}Na, but the half-lives of the last two are measured in seconds. If magnesium is bombarded with deuterons, that is, the nuclei of heavy hydrogen, consisting of one proton and one neutron, the result is ^{22}Na with a half-life of 2·6 years. We get other isotopes of sodium, ^{20}Na and ^{21}Na, by bombarding neon with protons, but they have short half-lives.

It is simple to look at the situation with the aid of nuclear equations. We cannot destroy mass, although we can exchange it for energy. We cannot destroy charge, but only redistribute it. The sodium nucleus has a charge of +11 because it contains eleven protons. A neutron has no charge and a mass of 1, a proton has charge 1 and mass 1, a deuteron has charge 1 and mass 2.

^{24}Na $\quad {}^{23}_{11}\mathrm{Na} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{24}_{11}\mathrm{Na}$

Radioactive sodium with one extra neutron

^{22}Na $\quad {}^{24}_{12}\mathrm{Mg} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{22}_{11}\mathrm{Na} + {}^{4}_{2}\mathrm{He}$

magnesium + deuteron = sodium + an alpha particle

^{21}Na $\quad {}^{21}_{10}\mathrm{Ne} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{21}_{11}\mathrm{Na} + {}^{1}_{0}\mathrm{n}$

neon + proton = sodium + neutron

^{20}Na $\quad {}^{20}_{10}\mathrm{Ne} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{20}_{11}\mathrm{Na} + {}^{1}_{0}\mathrm{n}$

neon + proton = sodium + neutron

These last two have such short half-lives – 22·8 and 0·3 seconds respectively – that they are only of academic interest. When they decay, a proton in the nucleus changes into a neutron with the emission of a positron. Hence it loses one unit of charge and becomes neon once again.

$$^{21}_{11}\mathrm{Na} - {}^{0}_{+1}\beta \longrightarrow {}^{21}_{10}\mathrm{Ne}$$

Some artificial radioisotopes

	Half-life	*Radiation*	*Produced from*
^{3}H	12·4 years	β only	^{6}Li
^{14}C	5770 years	β only	^{14}N
^{24}Na	15 hours	β and γ	^{23}Na
^{32}P	14·2 days	β only	^{31}P or ^{32}S
^{35}S	87·1 days	β only	^{34}S or ^{35}Cl
^{60}Co	5·25 years	β and γ	^{59}Co
^{110}Ag	253 days	β and γ	^{109}Ag
^{131}I	8·04 days	β and γ	^{130}Te
^{192}Ir	74 days	β and γ	^{191}Ir
^{198}Au	2·7 days	β and γ	^{197}Au

These and many others are produced in Great Britain by the Radiochemical Centre at Amersham. In some cases a simple chemical is produced or the radioactive material is left as the element, but very often the final result is a compound containing radioactively labelled atoms. For instance, $H_2{}^{35}SO_4$ or $Na^{131}I$. ^{14}C is made a constituent of a wide range of organic compounds such as drugs, and by this means it is possible to trace how they are distributed in the body. There is a large family of compounds labelled with ^{3}H (or tritium) and others labelled with ^{35}S or ^{32}P and so on.

Since radioactivity cannot be destroyed, and since it is possible to detect very small amounts of radioactive material by reason of the radiations they emit, radioisotopes can be ideal tracers, and this is one of the uses of radioisotopes which we will consider shortly.

Part 3
The radiations

α and β particles and γ rays are the only radiations we need consider as resulting from a radioactive change. It is possible to produce neutrons in some radioactive processes, notably the fission of ^{235}U, and there are ways in which neutrons are used apart from producing artificial radioactive materials. They have no electric charge, and they have a wide range of energies. They are not given off by any of the radioactive materials used in industry (although to be strictly and scientifically honest, one should say that a gram of uranium is likely to give out one neutron a second, which isn't much among its 700,000 α particles per second).

One thing we must get straight from the start is that the radiations from a radioactive substance do not necessarily make other substances radioactive. To suppose they did would be as sensible as saying that if you went out from a lighted room you would glow in the dark because light has been shining on you!

If an α particle hits an atom it is likely to bounce off. If it hits something its own size it will give up a lot of energy at each bounce. When it is going slowly enough, it will pick up two electrons and become a helium atom. This is what Rutherford demonstrated (see page 7). In air an alpha particle will travel a few centimetres, depending on its energy, and will hit over a hundred thousand atoms on its way. α particles would be stopped by a piece of thin paper.

β particles, being the same as electrons, bounce around from one atomic electron to another and lose energy in the process. They are deflected in many directions so it is difficult to measure the total length of their irregular path, but the actual distance travelled may be a few feet in air or a centimetre in water. If something is put in the way of a beam of β particles, less and less pass through to the other side as greater and greater thicknesses are put in the way. This fact is used in thickness gauges. When the β particle is slowed down sufficiently, it is captured by an atom which happens to be short of an electron.

A γ ray may give all its energy to an atomic electron and knock it out of the atom. If it has rather more energy, it may knock the electron out and carry on with less energy and repeat the process several times. A more energetic γ ray travelling near to a nucleus may use up all its energy in creating an electron and a positron. (This may be difficult to understand at this stage, but it is an example of the equivalence of mass and energy. If we destroy mass we get energy; in some circumstances we can produce mass from energy.)

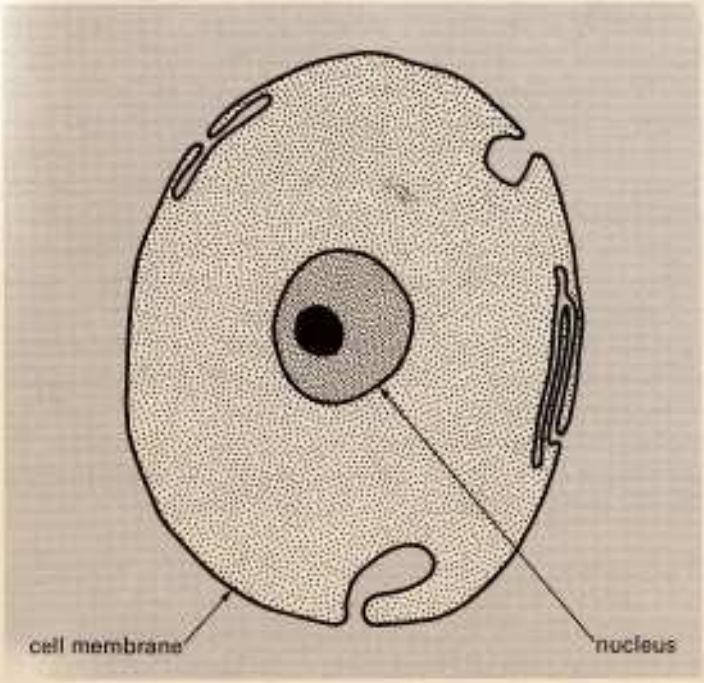
The final result of these interactions of radiations with matter is that a number of electrons have been dislodged from their atoms (i.e. the matter is ionized), and that the atoms themselves have been stirred up to faster movement, which means that heat is generated. It is possible to work out the heat produced from the rate of emission of energetic radiation. 1 curie ($3{\cdot}7 \times 10^{10}$ disintegrations per second) giving 1 MeV per disintegration is equivalent to 5·93 milliwatts. For instance, a 60,000 curie source of ^{60}Co gives out almost exactly the same energy as a 1-kilowatt electric fire. When the radiations from this enormous source, equivalent in radioactivity to about 130 pounds of radium, are stopped by the walls of the twenty-ton container which is needed for its safe transport, the outside of the container is warm to the touch.

What happens when radiations hit living matter? – Radiations have energy. If they can penetrate a living cell, they may deposit that energy in it, or in some part of it, and may damage it. This happens if we get too close to a hot object or absorb too

much radiation from the sun. Sometimes the cell recovers or is replaced, but sometimes enough damage is done to a large group of cells to harm the body.

It is rather like this with α, β, and γ radiations. They may pass through the walls of a cell and deposit energy in it. The cell has a small nucleus and is divided up into compartments by inner walls of proteinaceous material. In the cell is an aqueous solution, and in fact over 90 per cent of this is water! The whole lot is a rather delicate biochemical system.

If radiation enters the cell, there is just a chance that the nucleus may be hit, a greater chance that the inner walls may be damaged, and a prospect that ionization may bring about changes in the water such as $H_2O \longrightarrow H^+ + OH^-$ followed by $OH^- + OH^- \longrightarrow H_2O_2$.

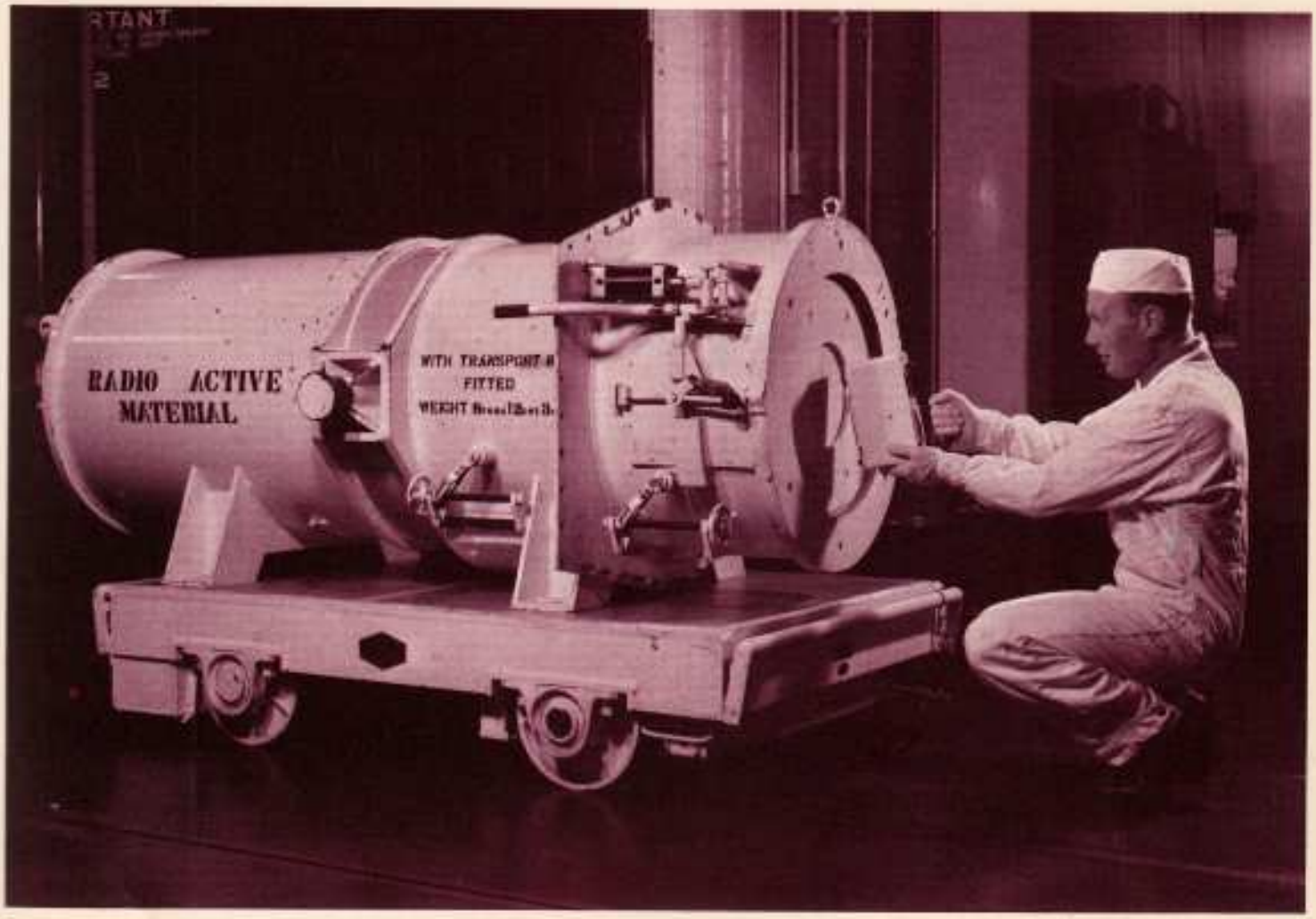


These factors may combine to upset the mechanism of the cell. It might be completely destroyed, or else the delicate mechanism of cell division may be upset.

Certain cells are more sensitive than others to radiation damage. A rapidly dividing cell is more likely to suffer damage than one which is static. It is possible to damage chromosomes and thereby cause mutations when the cell divides. This has been going on ever since living things existed, because radiation has always been with us. Other things, like certain chemicals, damage chromosomes, and some are far more effective than radiation in this respect so we can't blame radiation for every harmful change.

There is a background of radiation from naturally occurring sources and cosmic rays, and the use of radiation in industry has only added about 1 or 2 per cent to this (the U.K. Atomic Energy Authority has only been responsible for about 0·1 per cent of this percentage). Radiation in large enough amounts is harmful, so of course there are limits agreed internationally which govern how much radiation shall be allowed to the general public and to people working with radiation or radioactive materials. The unit adopted for measuring the amount of radiation absorbed is the *rad*. It is a measure of absorbed energy, and is equivalent to 100 ergs per gram. This is not very large when we think that 1 calorie, which is the heat energy needed to raise 1 gram of water 1 °C, is $4{\cdot}22 \times 10^7$ ergs. To make sure that no harm will be done by the extra radiation, it is agreed that the amount of radiation dose given to each member of the public should not exceed half a rad per year.

An example of the type of massive container required for the safe transport of radioactive fuel. A technician is checking for escaping radiations. *U.K. Atomic Energy Authority*



Part 6
Uses of radioactivity

We can exploit the fact that radioactive material betrays its presence by radiation and that the more radioactive substance is present, the more radiation will be emitted. In addition, we can exploit the penetrating power of the radiations or their effects on materials.

Tracers – Suppose we want to find how a piston ring in an engine wears. We could weigh it, use it for a few hundred hours and weigh it again, but this involves stopping the engine and it is difficult to repeat the conditions of testing. If the piston ring is made radioactive, however, the small particles which wear off are radioactive and will go into the oil system. If the oil is then made to pass through a detector of radioactivity, we have a measure of the amount of wear. It is easy enough then to see the effect of load or varying the temperature or the oil. Since the changes in wear are shown outside the engine as they occur, and the method is sensitive to small variations, it is quicker and more informative than the conventional one.

Radioactive isotopes in industry. Car components are irradiated in Harwell's BEPO reactor and then fitted by remote handling into the car. When the car has been run through various tests the amount of radioactivity in the lubricating oil is measured and the microscopic amount of wear is calculated. *U.K. Atomic Energy Authority*

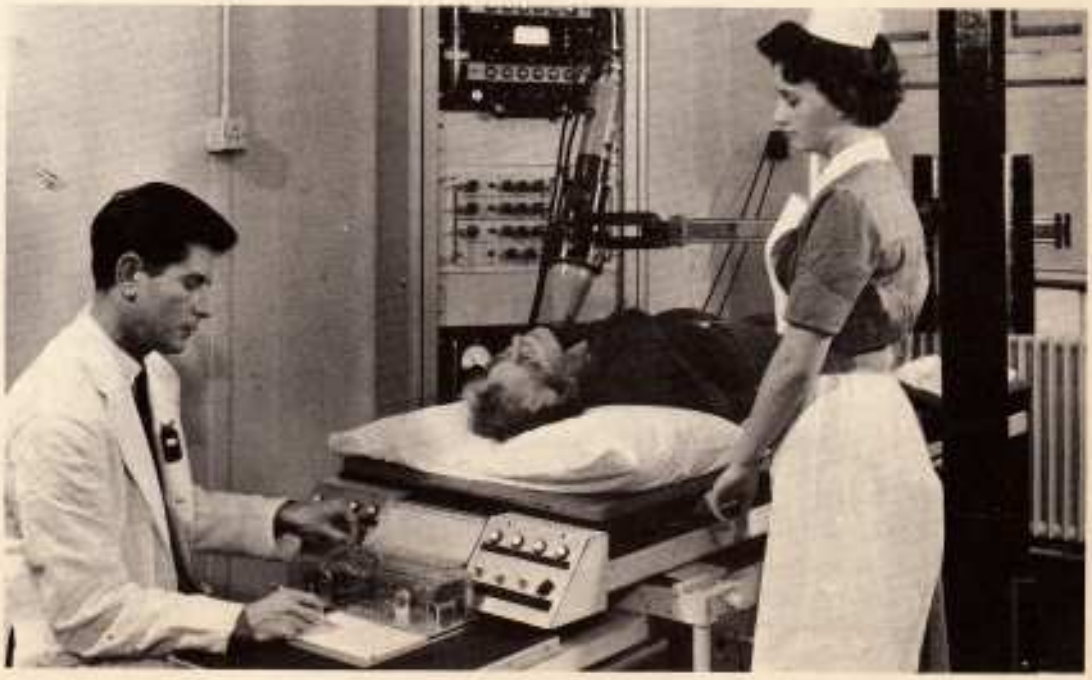
Again, suppose it is necessary to mix one substance with another to give a uniform product, how do we decide when mixing is complete? It is possible to take samples and analyse them, but that is very tiresome, and is very difficult if only a very small amount of, say, a trace element, is being mixed in. If it is possible to add some radioactive material, all that is necessary is to measure the radioactivity of successive samples and to continue mixing until the activity of successive samples is equal. This can often be done with simple apparatus and high accuracy. The method would not be used for production, but merely to set up the best conditions. If a radioisotope of short half-life, for instance ^{24}Na of half-life 15 hours, had

been used the activity after a week would be quite negligible and the product would be quite safe to be sold.

Here are a few further applications:

1. Typical question: 'Where is it?'
Mosquito larvae are grown in a solution of radioactive phosphorus. If the radioactive adults are released at one place and one checks mosquitoes trapped at different places for radioactivity, this gives important information about how far mosquitoes move from their breeding grounds.

2. 'How much goes this way and how much goes that way?'
a. Radioiodine in the thyroid shows how much of the substances manufactured by the thyroid in a given time stay put, go to the bloodstream, or go into the urine.
b. A labelled drug can show whether it goes where it should, or whether a significant amount goes where it could do harm to the patient.
c. Labelling a chemical makes it easy to measure its partition between solvents or its relative solubility in a variety of solvents, or at different temperatures.



Radioactive isotopes in medicine. To assess the position, size, and shape of the thyroid gland, a small dose of radioactive iodine is given to the patient. Iodine concentrates in the thyroid gland. The scintillation counter held over the neck is shielded with lead so that radiation only reaches it from a small area at the end of the pointed collimator which can be seen almost touching the neck. The patient is moved automatically to and fro and a colour picture of the gland is printed at the operator's end of the couch. *U.K. Atomic Energy Authority*

d. Labelled sewage has shown whether a particular disposal method causes bacterial pollution of a beach.

3. 'How much is there?'

a. Blood volume – a known volume of blood containing a radiotracer of known activity is injected. After letting it mix, a volume is drawn off and the new activity measured. If 1 microcurie ($2{\cdot}2 \times 10^6$ d/s) in 1 cm^3 went in, and 1 cm^3 taken out showed 250 disintegrations per minute, then the volume would be 2,200,000 ÷ 250 cm^3 or 8·8 litres. This is an example of dilution analysis and there are a host of examples – the amount of a particular constituent in a mixture, the volume of a lake, the volume of molten metal in a furnace, and so on.

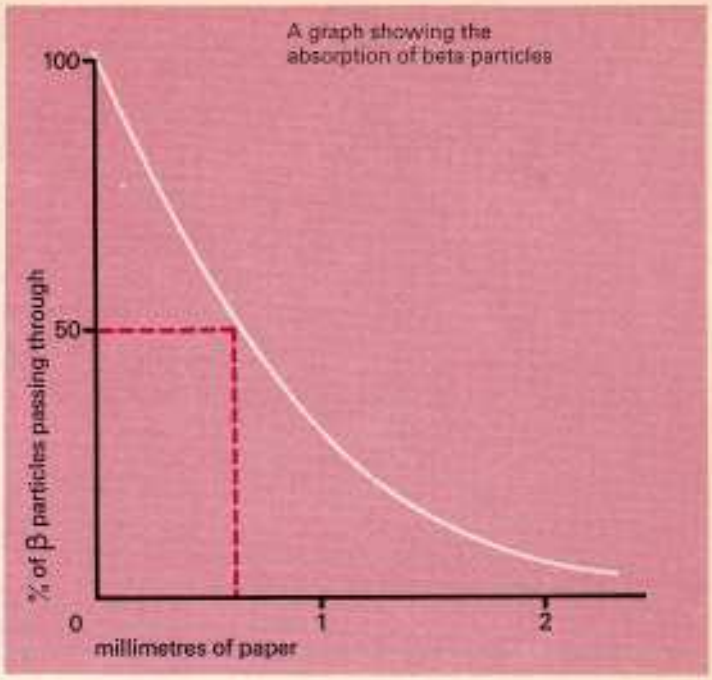
b. Flow of fluids. This could be a 'where is it' investigation, or a dilution. If some radioactive liquid is suddenly injected, it is possible to measure its rate of travel between points. If the size of, say, a pipe is known, the volume flowing is known. By another method, active solution is put in continuously and a sample taken downstream. The activity will be diluted and one can calculate the rate of flow.

Detection of leaks in a buried pipe – This is done by putting some short-lived radioactive material, for instance ^{24}Na as sodium carbonate, into the leaky pipe and making it flow through a section under pressure. The solution is made to pass out of the end of the pipe but it has leaked into the earth where there were holes or bad joints. There are various methods of detecting where the radioactive solution has leaked from the pipe. In one, radioactive markers (generally of ^{60}Co) are put at known distances. The detecting device consists of Geiger counters which feed their pattern of detected pulses into a wire recorder (a version of a tape recorder). The whole is contained in a waterproof cylinder which is either forced along the pipe by the water after the radioactive solution has been flushed out, or, for short runs, pulled through. When the record is 'played back' and put on a chart recorder whose paper chart moves at a known steady rate, a line will be traced which shows the position of the leaks in relation to the places where the markers were put in, since the radioactive sodium salt will have been absorbed by the soil where the leaks were. Modern developments of this permit the examination of many miles of new pipeline, and the method is now well established.

Blood flow - Sometimes there is a restriction of the blood circulation. By injecting a small amount of radiosodium, the rate of flow between points can be measured and compared. Again, in the case of a skin graft, the blood flow into the new area can be determined. By choosing the appropriate radioactive material, often as a radioactively labelled compound which has been synthesized, the functioning of many body organs may be checked.

Plant studies – Radioactive labelled nutrients can help the plant physiologist to study the rate and method of uptake of fertilizers and trace elements, and he can study photosynthesis by growing plants in an atmosphere of $^{14}CO_2$.

These are only a very few of a large number of tracer applications. They may show you that they are a powerful tool of research and technology. An excellent book which takes the story further is *Isotopes* by Dr J. L. Putman (Penguin Books). This deals also with other uses of radioisotopes, which will only be briefly mentioned here.



Analysis – We have already seen that by adding a radioisotope and measuring the diluted activity, we can measure volumes, the amount of particular constituents, and the like. If we irradiate two small masses of an element in a reactor under exactly the same conditions, the only thing which makes their activities different is their difference in weight even when the element is in chemical combination with other elements. Thus if 1 mg of copper were irradiated and showed an activity measured as 60,000 counts per minute and an unknown weight irradiated with it gave 36,000 counts per minute, both of these measurements being made with the same detector and both being proportional to the actual radioactivity present, then we could say that the second weight was 36,000 ÷ 60,000 or 0·6 mg. In practice, it is possible to determine copper in amounts of about 10^{-10} gram (0·0001 microgram), and to be quite sure that it is copper because of the half-life and energy of the radiations from radioactive copper.

Since there are some seventy elements which can be determined in amounts which are a very small fraction of a microgram, this is clearly a powerful new tool for the analyst. An important advantage is that we can be quite sure what we have got, and any impurities which get in during chemical extraction or manipulation make no difference because they are not radioactive. Sometimes it is not necessary to do any chemistry to get the answer, and in fact the irradiated material remains as it was before irradiation. This has been done to find arsenic in hair or nail clippings, or to identify trace elements in dust so as to prove its origin. Thus not only does the chemical analyst have a sensitive and accurate new method, but the criminologist and forensic chemist have a new device to fight crime.

Using a reactor like 'BEPO' at Harwell it is possible to determine arsenic, gold, and many of the rare earths down to 10^{-11} gram, a whole range including antimony, cobalt, copper, phosphorus, and manganese to 10^{-10} gram, and most of the common elements in amounts between 10^{-9} and 10^{-7} gram. The method is used for very small samples or for special investigations, and, most particularly, in order to check the accuracy of other methods like colorimetric determinations, which are simpler and do not need a reactor.

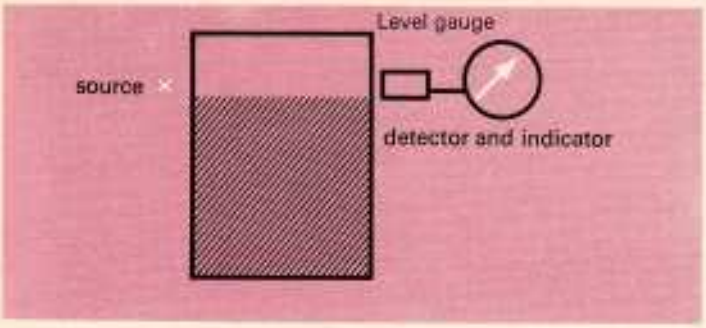
Gauges – How do you measure the thickness of a piece of paper? Use a micrometer? Count a large number of sheets and measure with a ruler? Cut a piece and weigh it and work it out from density and area? These methods would do, but they wouldn't be convenient if paper were being made by the mile, a few yards wide. (The third method was used until a few years ago, and is still used for an ultimate check, and to calibrate other methods.)

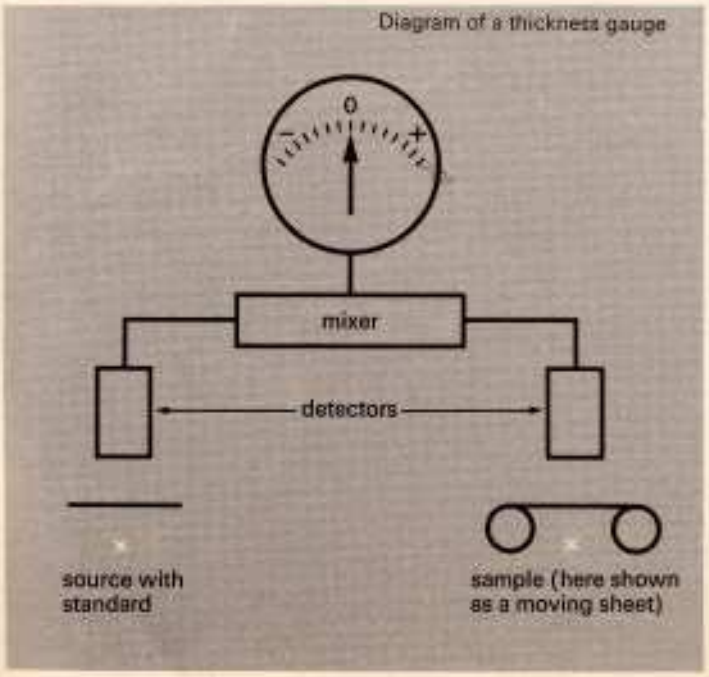
Now β radiation is absorbed by material, and the more material, the more absorption. Therefore if we set up a radioactive source on one side of the sheet and a detector on the other, the number of β particles which pass through is a

Using a level gauge to find the level of CO_2 in cylinders. *U.K. Atomic Energy Authority*

A gauge being used to measure the thickness of a pipe. *U.K. Atomic Energy Authority*

A gauge being used to measure the thickness of zinc coatings on steel. *Burndept Limited*





measure of the thickness. Nothing touches the sheet, so it could be moving rapidly. As well as this, the signal given from the detector that a greater or lesser number of particles is getting through, can work a meter or a recorder, or control the process which governs the thickness. Often the thickness is compared with a standard, so the indication is given as the deviation from this. Over the past 10 or 15 years gauges have been developed and are in use in many industries for controlling the thickness of paper and plastic sheet, sheet metal, or the packing density of tobacco in cigarettes (which are made in a long continuous tube). None of these materials becomes radioactive of course: this could only happen if radioactive material were transferred, but as radiations are the only things which pass, there is no radioactivity induced.

As a slight variation on this, but still in the field of gauging, we can consider level gauges and empty packet detectors. The first could be used as a convenient method of indication or even of control of the level of liquid in a closed vessel. It has been used to find how much fire extinguisher fluid there is in an appliance or how much of a liquefied gas is present in a vacuum vessel. We just need a source of radiation and a detector. The same principle applies to empty package detectors. The gauge can be set to reject an unfilled package (packet of pills, tin of paint – in fact almost anything which is filled in an automatic plant), or it could be set to reject partially filled containers. Since the scheme needs no contact or weighing, and can work fairly fast, it is much used in industry.

Other ways of using radiations – Beta and gamma radiations are scattered by the electrons of the atoms in their path, and sometimes are sent back the way they came. The amount which comes back depends on the nature of the material which is causing the scattering. This is used to measure the thickness of plating on metal and it is the principle which guides an automatic coal cutter to remove coal and to turn aside from the rock which is above and below it.

Gamma radiation passes through metals and is reduced in intensity more or less, according to the thickness of the metal or its nature. If there were a hole or a piece of slag, this would alter the amount of radiation passing through locally. If a photographic film is put the other side, the 'radiograph' which is produced gives information about flaws, variations in thickness, and so on, just as an X-ray machine would. It takes

Using a cobalt 60 source to photograph the welded seam of a three-inch-thick steel belt for a boiler drum. In this way faults in the welding can be detected. *U.K. Atomic Energy Authority*

longer to get a gamma radiograph than an X-radiograph, but very often it has a number of advantages, and among them are cheapness and simplicity.

If a large dose of γ radiation passes through bacteria, they are killed. They need about 2·5 million rads for a fairly certain 'kill', but higher, more complex living systems are destroyed by less. (Animals, including man, cannot long survive 1000 rads; weevils and cockroaches are killed by a few tens of thousands of rads.)

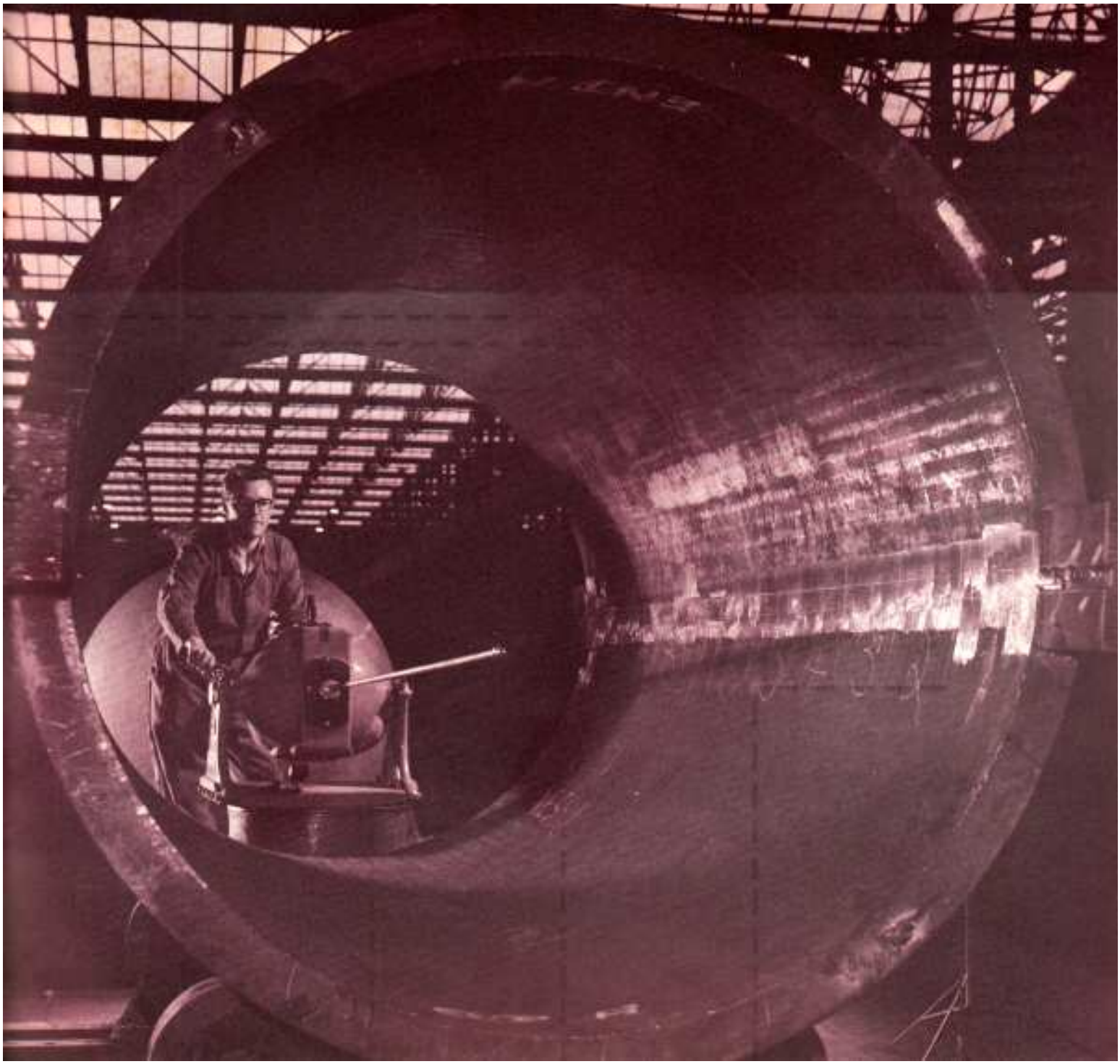
A very important use of radiation is for the sterilization of medical items – hypodermic syringes, for instance, which can be made for a few pence and are thrown away after use. (This obviates the need for a steam sterilizer, and reduces the risk of cross infection.) Many other items such as drugs which would be damaged by heat, sutures, scalpels, and more complicated devices are also dealt with similarly. The type of plant used commercially, is very heavily shielded and is provided with safe methods for getting the materials for sterilization in and out. It may contain a few hundred thousand curies of ^{60}Co, and there are foolproof methods for ensuring that the source is safely stowed before anybody can enter. Items for sterilization are usually packed in individual, sealed plastic bags, and a batch of these goes through the plant together with a 'tally' which changes colour in a significant way when it has had a sterilizing dose of radiation. It should be obvious from what has been said previously that passing radiation through these materials will not make them radioactive. Many millions of items have been sterilized this way, and it is already rare to find a doctor using the older type of hypodermic syringe, for instance, since the plastic one in its envelope labelled 'sterilized by gamma radiation' is usually much preferable in every way.

Beams of γ radiation are used for therapy instead of beams of X-rays when deep penetration is needed. Fixed sources in parts of the body can give similar radiation treatment to that given by radium. The cost is negligible, and suitable sources are very readily available for the specialist hospitals to use.

Conclusion – We started this book by looking at how our knowledge of the nature of radioactivity was built up. We then discussed the various phenomena associated with the radiations from radioactive materials.

Radioactivity would have been little more than an interesting branch of physics with a certain amount of chemistry if it had not been for the very great increase in the availability of artificially produced radioactive elements which have been available for the past 15 to 20 years from the irradiation of material in nuclear reactors. This development has provided a great number of new tools for research, medicine, and industry. Along with this expansion has been a development of understanding about how to control hazards from radiation.

We have only briefly mentioned a very few ways in which radioactivity is being used, but I hope we have seen how far we have come in the seventy years from the days of Madame Curie and Becquerel.



Chemistry Background Books
General editor H P H Oliver Author of this book R A Faires
Art editor Ivan Dodd
Published for the Nuffield Foundation by Longmans Penguin Books
Longmans Green and Co Ltd 48 Grosvenor Street London W1
Penguin Books Ltd Harmondsworth Middlesex England
 First published 1968
Made and printed in Great Britain by W S Cowell Limited

CBB04339