Chemistry Background Book

Inside the Atom

Dalton's solid atom is an atomic model that we still frequently use, for example, in this representation of a sulphur molecule.

Part one Opening up the atom

For almost a hundred years after John Dalton put forward his atomic theory, people thought of atoms as solid indestructible particles. They had no reason, and no experimental evidence, to think otherwise. And although we have now learned much more about atomic structure, and although our model of the atom is no longer that of a solid particle, Dalton's original idea remains a useful one. In all the chemistry you have studied so far, for example, the solid atom has been a perfectly adequate basis to understand chemical behaviour – to explain reactions in terms of rearrangement of the atoms and to arrange a periodic table of the elements based on their atomic weights. In much (but not all) of the chemistry you will do in the future, it will continue to be adequate. Dalton's model of the atom is simple. That it is too simple – that it will no longer explain everything we know about the behaviour of substances – is no reason for getting rid of it.

The size of the atom – Dalton imagined that atoms were the ultimate particles into which matter could be broken down and that particles smaller than the atom did not exist. He also believed the atoms of each element to be exactly alike and to differ from those of all other elements. He thought this difference showed itself chiefly in respect of atomic weight, with hydrogen atoms the lightest of all. Chemists immediately set about finding these atomic weights. How they did so makes a fascinating story, but it is not one that we can cover here. At an important conference held at Karlsruhe in 1860, scientists agreed on fairly reliable estimates of the atomic weights of the elements known by then – about sixty of them.

These atomic weights, however, did not represent the actual weight of the atoms. They showed, for example, how much heavier an oxygen atom was than a hydrogen atom or

John Dalton (1766–1844) first introduced the idea of the atom into chemical explanation. *National Portrait Gallery*

how much heavier a chlorine atom was than an oxygen atom: they did not show the absolute weight (the weight of a particular atom in millionths of a gram) of any of them. In other words, they were relative weights, relative to the hydrogen atom as 1.

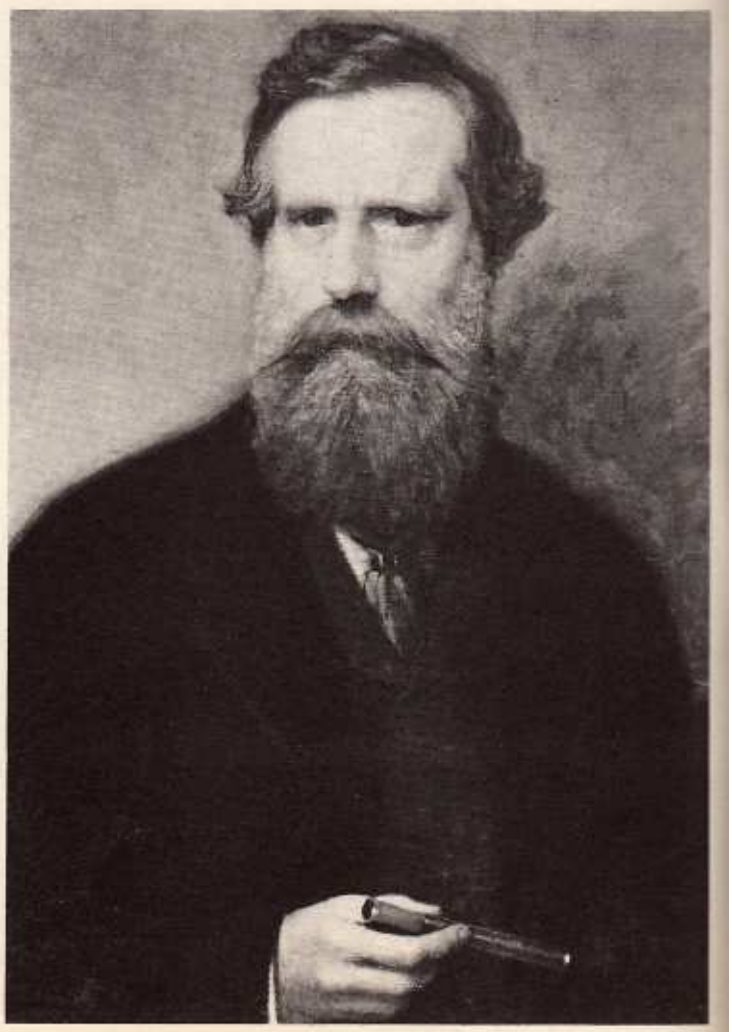
In about 1865 the absolute weights of atoms were determined by calculating the number of particles in a fixed volume of gas. These calculations showed that the atomic weight of an element in grams (gram atomic weight) contained something under a million million million million atoms – as we now know precisely, using such accurate methods as X-ray diffraction, $6{\cdot}023 \times 10^{23}$ atoms. This number is called Avogadro's Number, after the Italian scientist Avogadro. In 1811 Avogadro put forward the principle that equal volumes of all gases at the same temperature and pressure contain the same number of molecules. Since 1865 Avogadro's Number has been experimentally verified in several different ways. The gram atomic weight divided by Avogadro's Number shows the absolute weight of an atom to be extremely small.

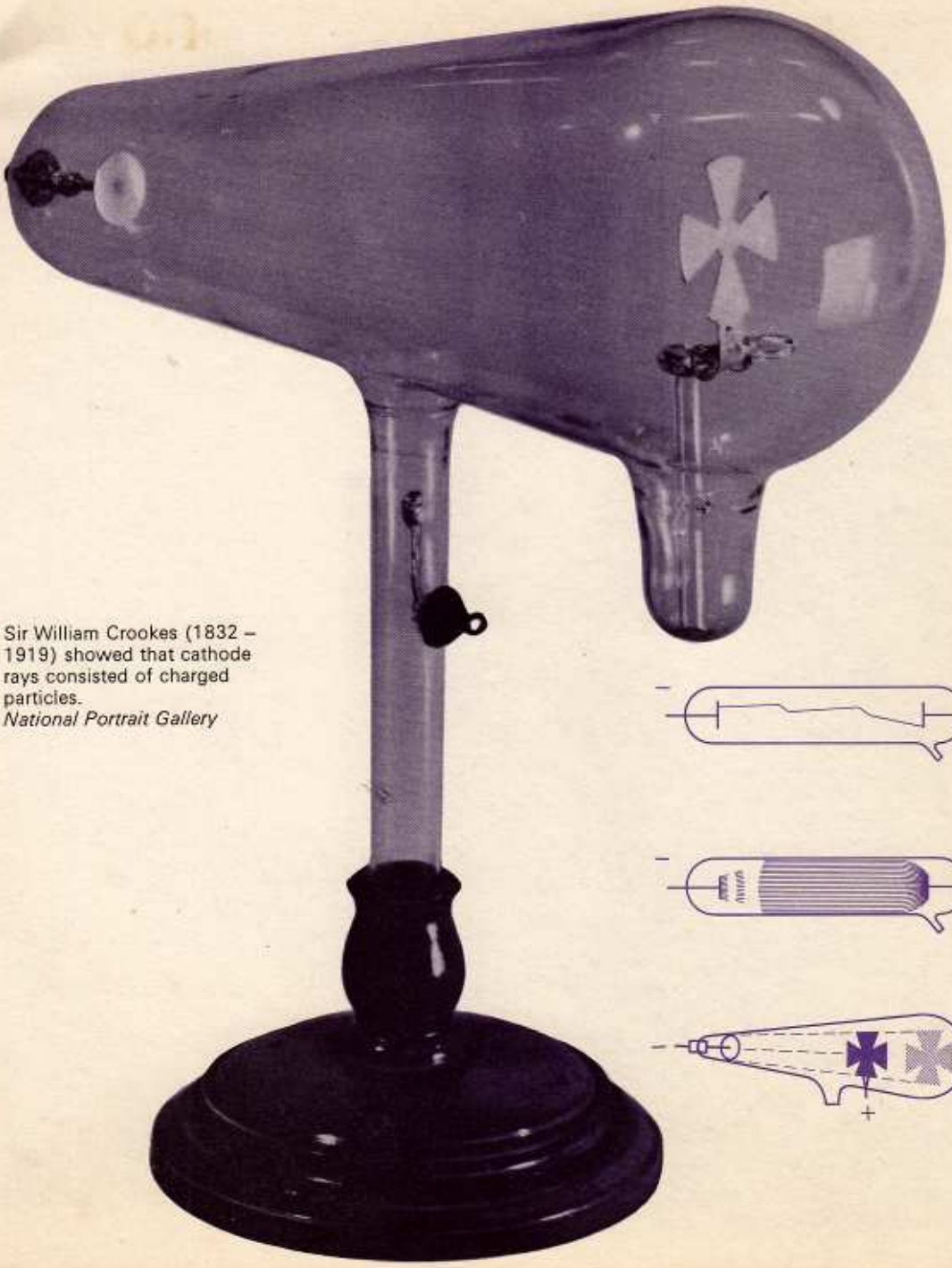
Smaller than the atom – The first step leading to the idea that atoms might not be the ultimate particles of matter, solid and indestructible, was the discovery of the electron – a 'particle' very much smaller than the atom itself. The discovery came about from experimental work by scientists on the passing of electricity through gases.

At normal pressures, gases are poor conductors of electricity. But when an electric current is passed through a gas at low pressure (see the pictures of a vacuum tube) a thin zig-zag spark darts between the two electrodes. As the pressure is further reduced a bright column of light fills the tube. The colour of this light depends upon the chemical nature of the gas – sodium gas is yellow; neon is red. You will have seen lighting of this kind in street lamps, in shop and advertising signs, and sometimes in houses. Finally, as the pressure is even further reduced – to about $\frac{1}{2}$ mm of mercury – the bright column of light recedes towards the anode, and the glass opposite the cathode begins to glow. You will have seen this glow too – on the screen of a television set. For a television tube contains gas at a very low pressure through which an electric current is passed.

Long before television, in 1869, Hittorf showed that a solid object placed in front of the cathode casts a shadow on the glass. Evidently the glow was caused by rays streaming from the cathode. A few years later Sir William Crookes found that these cathode rays could be deflected with a magnet. He therefore concluded that they were not light rays, as had been originally supposed, but were electrically-charged particles – subsequently found to be negatively charged.

In 1897 Sir J. J. Thomson carried out some experiments on these negatively-charged particles at the Cavendish Laboratory in Cambridge. As a result of these experiments he





One of Crookes's vacuum tubes with which he confirmed Hittorf's experiment that a solid object (here a Maltese cross) placed in front of the cathode cast a shadow on the glass opposite. This experiment demonstrated that the glow on the glass was caused by 'rays' coming from the cathode.
Crown Copyright. Science Museum, London

Sir William Crookes (1832 – 1919) showed that cathode rays consisted of charged particles.
National Portrait Gallery

Discharge of electricity through a gas as the pressure is reduced. At a pressure of about 50mm of mercury, a thin zig-zag spark passes between the two electrodes.

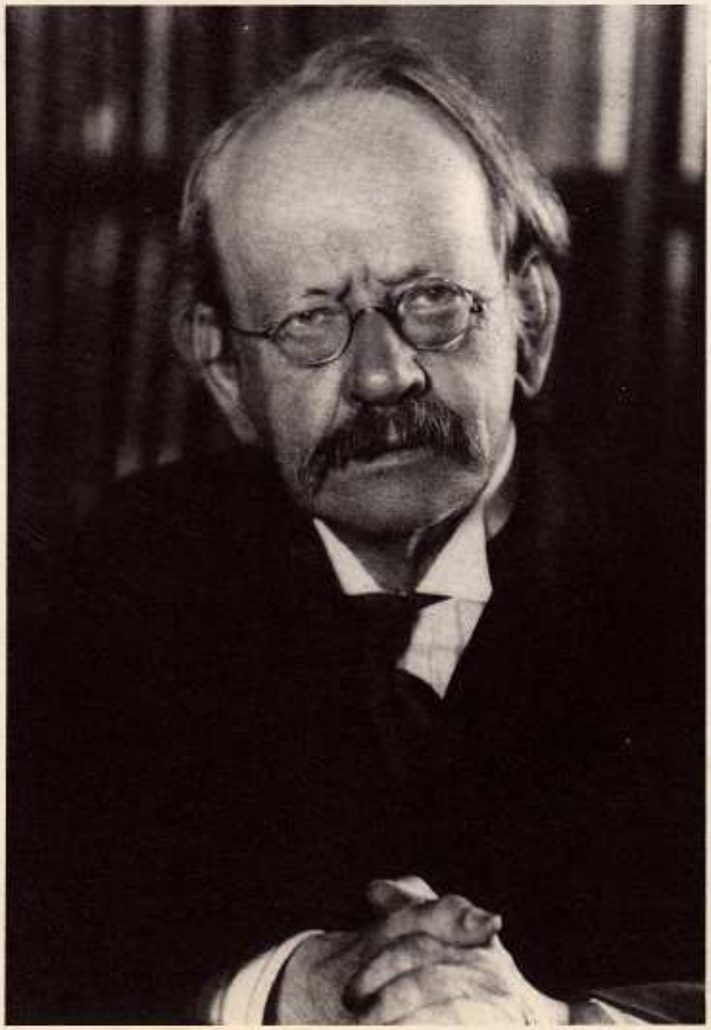
At a pressure of about 10mm of mercury, a bright column of light fills the tube.

At a pressure of about ½mm of mercury, the column of light recedes towards the anode, and the glass opposite the cathode begins to glow. An object (such as a cross) placed in front of the cathode casts a shadow on the glass.

arrived at a rough value for the mass of the electron. This was very small – about two thousand times less than the mass of the smallest atom, hydrogen.

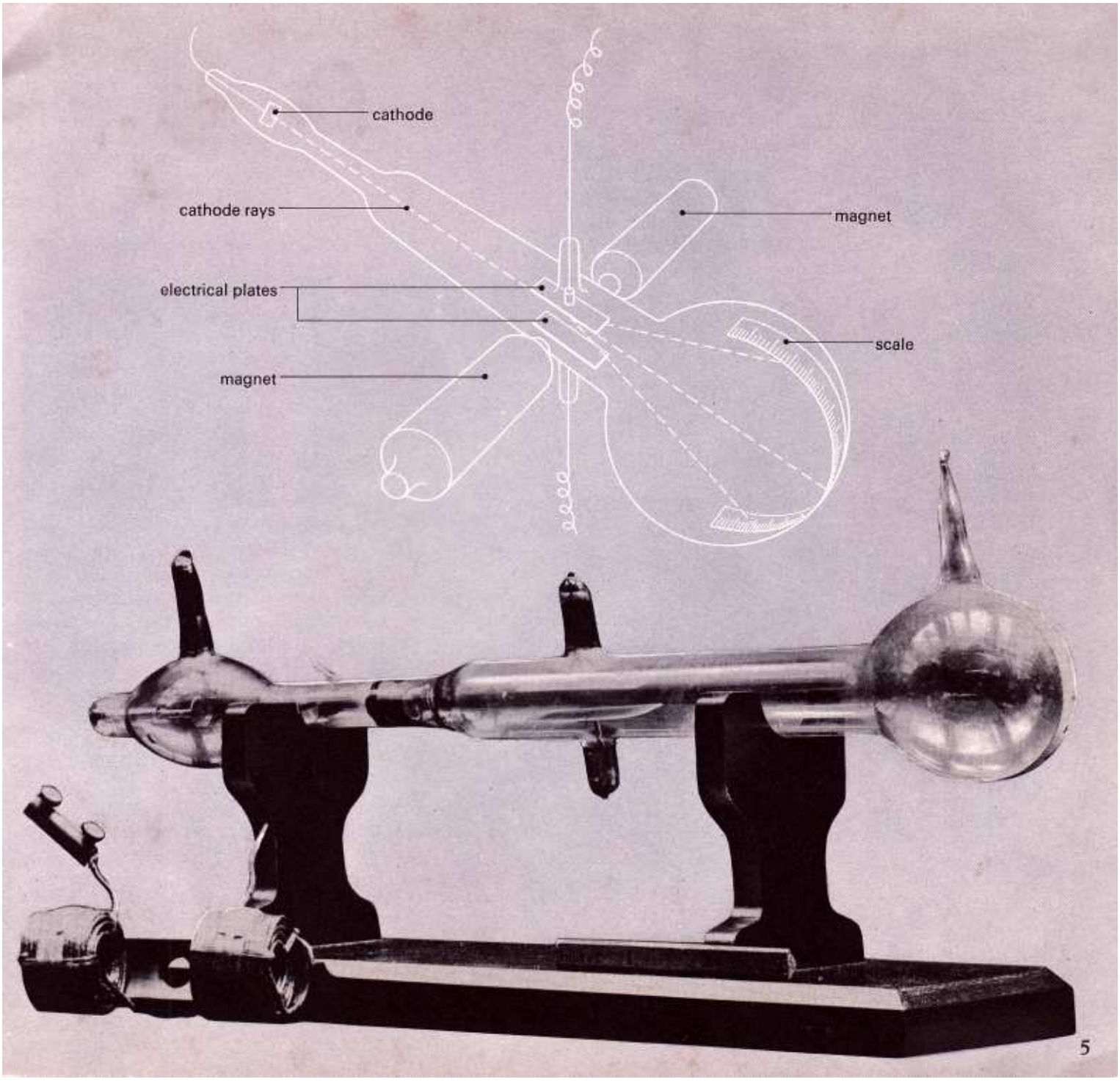
Radioactivity – Contemporary with the first work on the nature of the electron, another big step towards opening up the structure of the atom was the chance discovery of radioactivity by Henri Becquerel in 1896. Becquerel, who was examining the nature of fluorescence, happened to have some uranium salt in a drawer on top of a photographic plate. To

Diagram of a vacuum tube for measuring the ratio of the charge of an electron to the mass. The cathode rays (electrons) pass along the tube through magnetic and electric fields at right-angles to each other. The deflection of the rays is observed on the scale surrounding the large bulb.



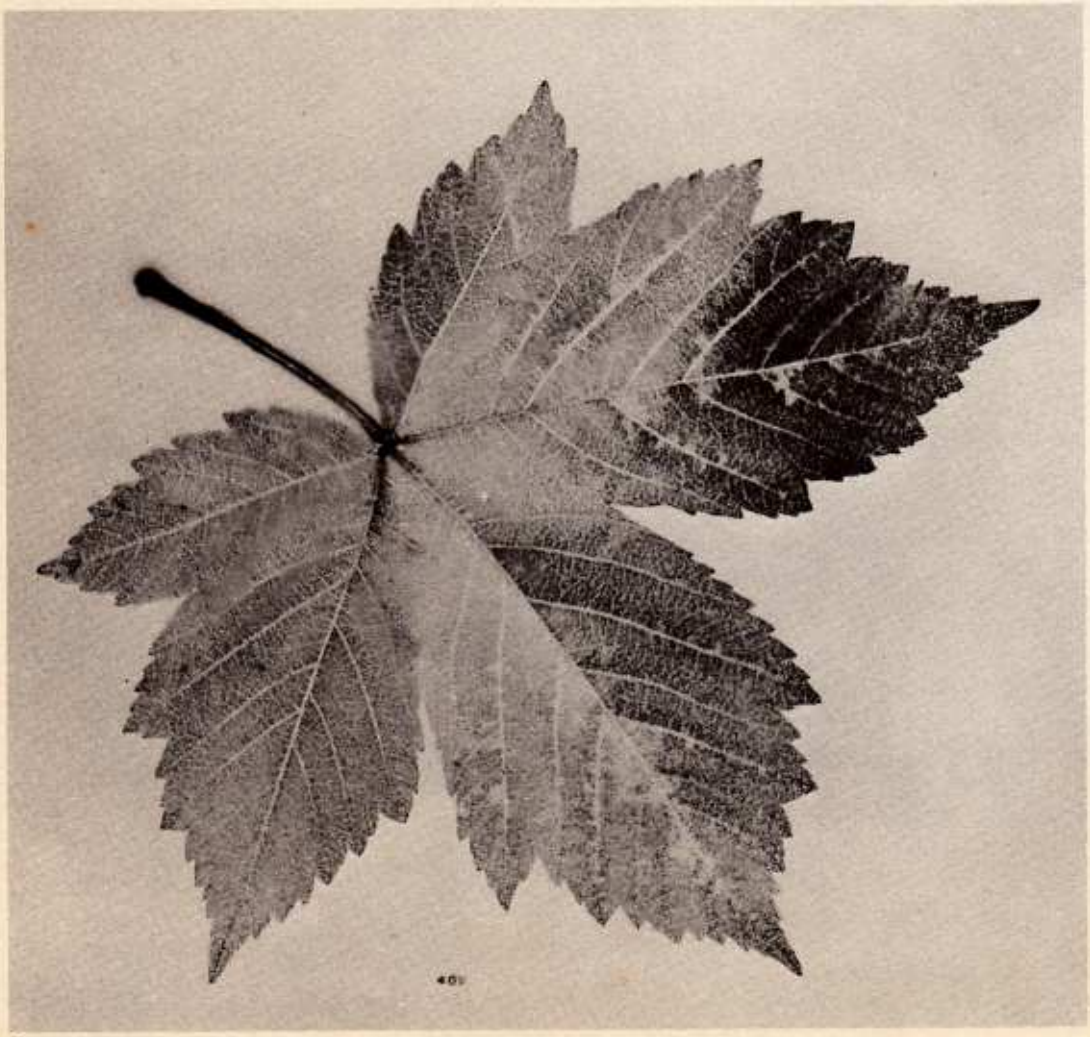
Sir J. J. Thomson (1856 – 1940), the discoverer of the electron.
Elliott-Fry

Thomson's original vacuum tube in which he measured the ratio of the charge on an electron to the mass.
Lent to the Science Museum, London, by the late Lord Kelvin


cathode
cathode rays
magnet
electrical plates
scale
magnet

Henri Becquerel (1852 – 1909), discoverer of radioactivity.

A reconstruction of Becquerel's original experiment. The photographic plate, at the bottom of the dish, became fogged – although it was covered from the light with paper. Becquerel therefore concluded that the fogging must be due to the uranium compound lying on top of the plate.
U.K. Atomic Energy Authority



Objects containing radioactive substances will take their own photographs. This is an autoradiograph of a sycamore leaf that has absorbed radioactive substances. Radiography has become a useful technique for exploring beneath the surface of things, for example, how substances are distributed in living organisms.
U.K. Atomic Energy Authority

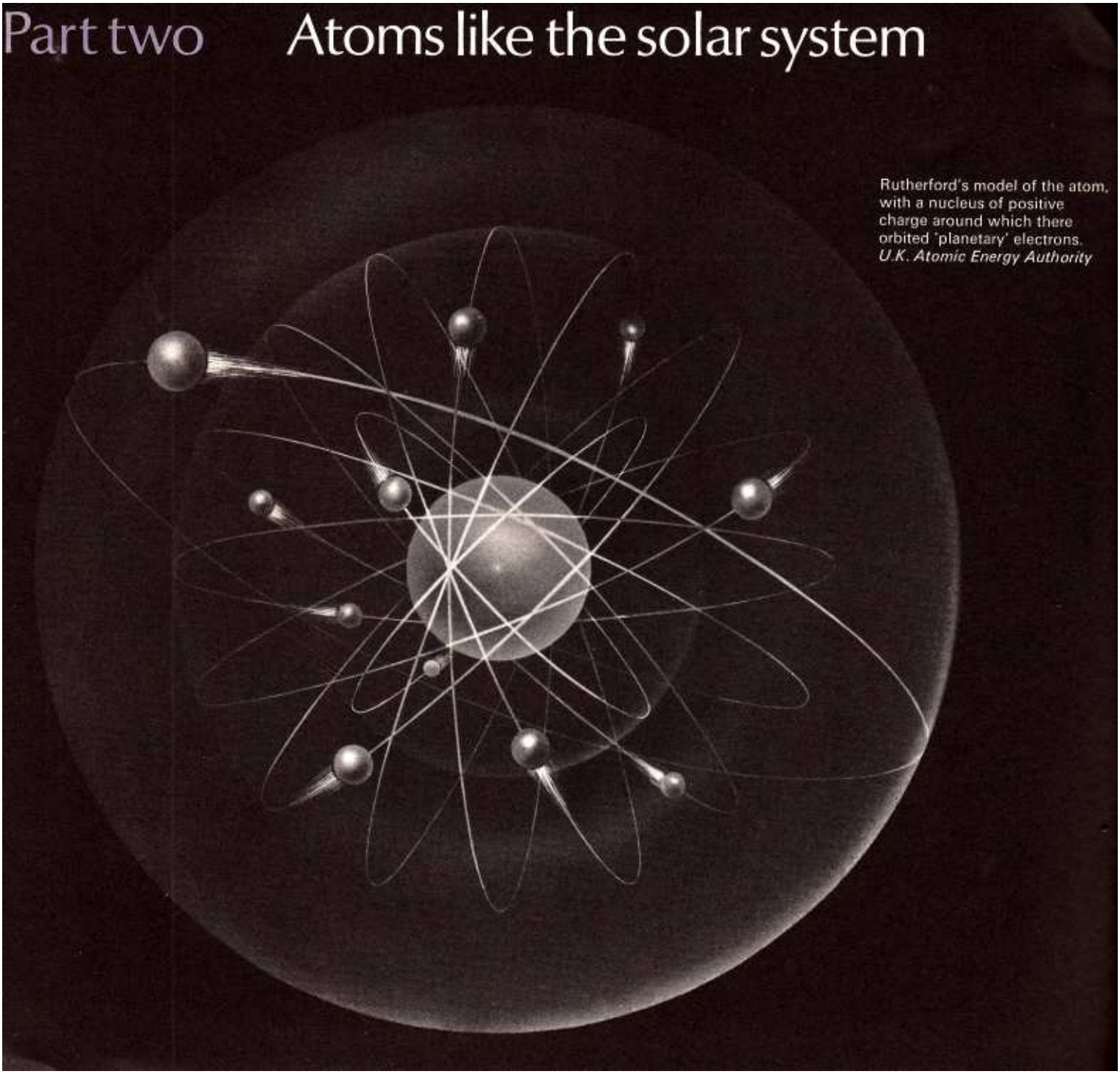
his surprise he later noticed that the plate had become fogged, though it had not been exposed to light. He therefore concluded that the uranium salt must be emitting rays and, working with Madame Curie, he found that this emission of rays – called radioactivity – was also a property of the element thorium. Shortly afterwards, Madame Curie and her husband Pierre isolated two more radioactive elements: polonium and radium.

On examining the rays emitted by radioactive substances, scientists found that they were of three distinct kinds: α rays which were positively-charged particles of about the same mass as a helium atom (the next lightest atom to hydrogen); β rays which were negatively-charged particles identified with the electrons that had been found in cathode rays; and γ rays which were high-energy waves similar to the X-rays that had been discovered by the German Wilhelm Röntgen in 1895. But where, people wondered, were these particles and rays coming from?

To explain the origin of radioactivity, the New Zealander Ernest Rutherford and the Englishman Frederick Soddy suggested that the particles and rays resulted from the breaking-down of the atoms of the radioactive elements to form other simpler elements. If their theory was acceptable it meant that not only were some elements unstable but also some atoms were not indestructible.

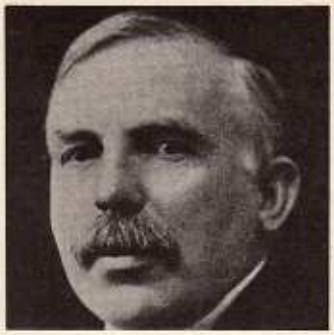
Marie Curie (1867 – 1934) and Pierre Curie (1859 – 1906), the discoverers of the radioactive elements polonium and radium.

Part two Atoms like the solar system



Rutherford's model of the atom, with a nucleus of positive charge around which there orbited 'planetary' electrons.
U.K. Atomic Energy Authority

Baron Rutherford of Nelson (1871 – 1937) who, among his many achievements, established the nature of radioactivity, put forward a nuclear theory of the atom, and carried out the first artificial transmutation of one element into another.
Walter Stoneman



Niels Bohr (1885 – 1962) worked out fixed orbits for electrons round the nucleus in the Rutherford model of the atom.
Fox Photos

The Rutherford atom – Elements had been discovered that emitted electrically-charged particles. This led to the idea that atoms might be built up of these particles. Scientists devised models to show what they thought the structure of the atom was like. Among the various atomic models put forward was that of J. J. Thomson's 'plum pudding' in which electrons were embedded like currants in a sphere of positive electrical charge. But it remained for Rutherford to come to grips with the problem.

Lord Rutherford was one of the greatest scientific experimenters ever. In 1911 Marsden and Geiger, two members of the Physics Department working under Rutherford at Manchester University, carried out a famous series of investigations into the structure of the atom. They directed α particles from a radioactive element at a target of very thin gold foil. To find out the effect of the foil atoms on the high-speed positively charged α particles, they placed behind the foil a screen coated with phosphorescent zinc sulphide. What this screen is and why they used it needs some explaining. In all experiments aimed at probing the secrets of the atom there is the problem that individual atoms are far too small to see, even today with the highest-powered microscopes. However, it is often possible to reveal the presence of atoms or of atomic particles indirectly. The phosphorescent screen, when it is struck by an α particle, produces a tiny scintillation of light which can be seen through a microscope. You can see this effect yourself if you look at the hands of a luminous watch through a powerful lens. By observing the scintillation on the phosphorescent screen, it is possible to tell through what angle an α particle has been turned. (Another instrument for observing indirectly the effect of atomic particles is the cloud chamber – see overleaf.)

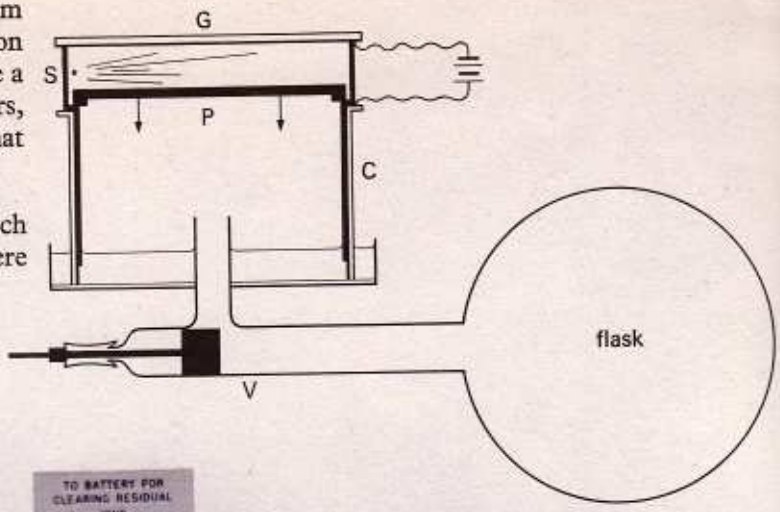
It was found that most of the particles passed through the gold foil with only minor deflections. This was as Rutherford had expected. A few α particles, however, were turned through a very large angle, and occasionally an α particle bounced back. Commenting on this, he said: 'It was quite the most remarkable event that ever happened to me in my life. It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you.' To account for this 'remarkable event', Rutherford formed the idea of a nucleus of concentrated positive electrical charge at the centre of each gold atom. Should a positively-charged α particle collide directly with a positively-charged nucleus, this would explain why the α particle was being repelled. However, because most of the α particles passed through the foil with only minor deflections, Rutherford concluded that there must be a relatively large area of 'empty' space surrounding each nucleus. Also, in so far as most atoms are electrically neutral, he proposed that a sufficient number of electrons to balance the positive nuclear charge revolved around the nucleus in the empty space – they would have to be revolving or otherwise they would be attracted into the nucleus. Rutherford's model of the atom has often been likened to a miniature solar system, with electron planets revolving round a nuclear sun. It was no longer a solid atom but it was still fairly simple.

Shortly after Lord Rutherford proposed his model for the atom, the Danish scientist Niels Bohr introduced some refinements. He worked out fixed orbits round the nucleus for each electron, based on the calculated energies of the electrons.

The Rutherford model of the atom provided chemists with a new insight into the way substances behaved. It explained, for example, the formation of charged atoms (or 'ions' as

they are called) by the loss or gain of one or more electrons. Thus, in the formation of sodium chloride, each sodium atom loses an electron to become a positively-charged ion or cation (Na^+), and each chlorine atom gains an electron to become a negatively-charged ion or anion (Cl^-). Within a few years, however, the idea of a solid electron proved as illusive as that of a solid atom.

The electron cloud – In 1897 the German physicist Heinrich Hertz had shown that if solids (especially metals) were



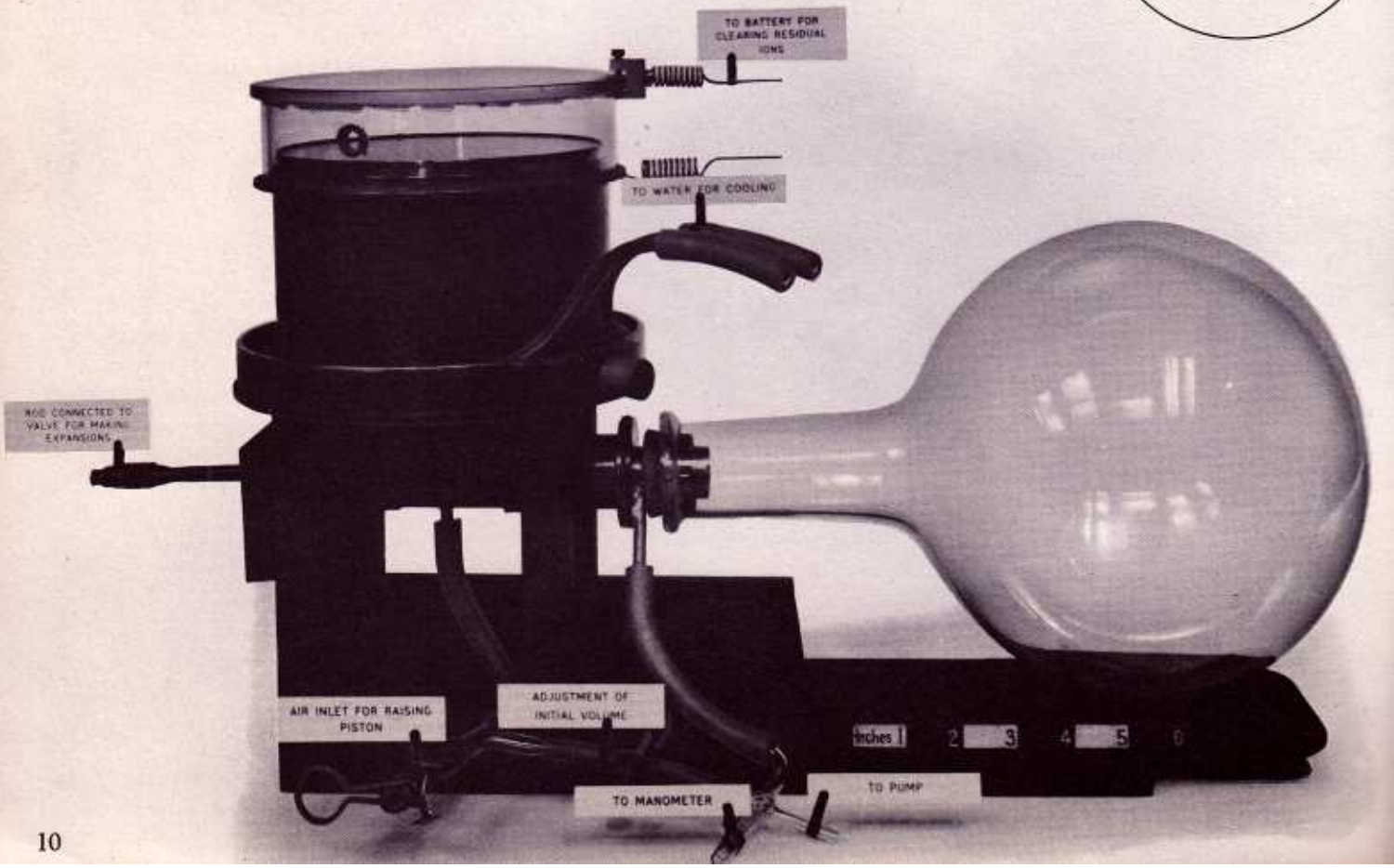
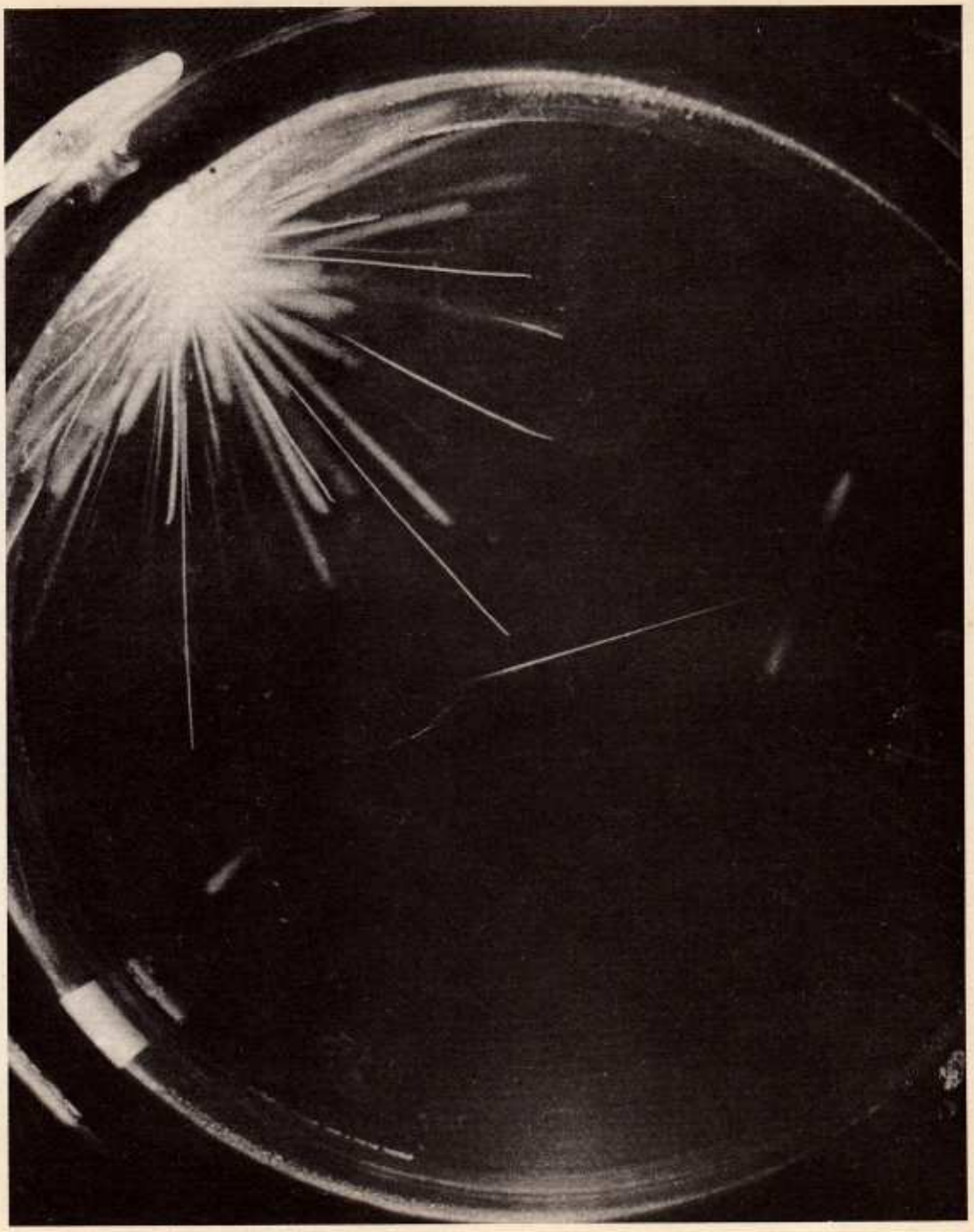


Diagram of a Wilson cloud chamber – The chamber (C) is covered with a glass plate (G), and the gas in the chamber is saturated with water vapour. If the circular piston P is dropped a short distance (by opening the valve V connected to the evacuated flask), the pressure of the gas falls and it becomes supersaturated with water vapour. An α particle from the sources ionizes the gas molecules in its path, and the supersaturated water vapour condenses on these ions, leaving a visible trail behind the α-particle.

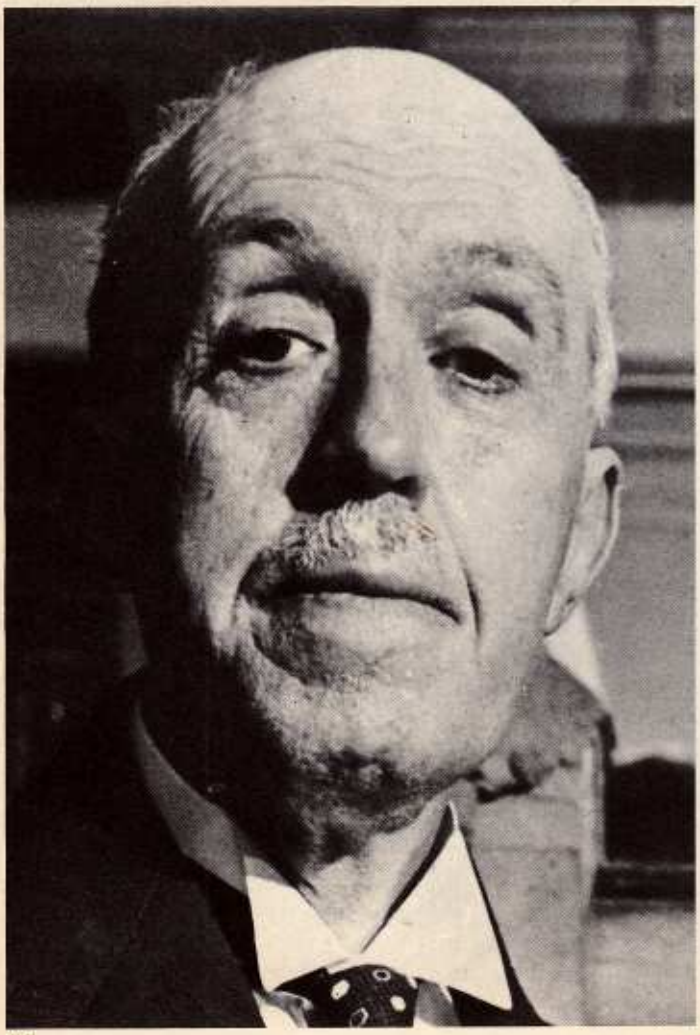
The original cloud chamber invented by C. T. R. Wilson (1869 – 1959).
Science Museum, London. By courtesy of the Cavendish Laboratory



A fan of α particles photographed in a cloud chamber by C. T. R. Wilson.
Crown Copyright. Science Museum, London

Diffraction patterns produced by electrons passing through a very thin film of gold. Photographs like this provided experimental evidence that electrons have wave, as well as particle, properties.
Science Museum, London. By courtesy of Professor Sir George Thomson, F.R.S.

Prince Louis-Victor de Broglie (born 1892), the first to suggest that electrons might show wave behaviour.



irradiated with ultra-violet light they emitted electrons – the light was 'knocking' the electrons out of the metals. This effect could not be explained on the basis that light consisted solely of waves, as had been originally supposed. Albert Einstein, following up an idea which Max Planck had put forward at the turn of the century, suggested that light consisted of packets of energy which he called photons. In other words, light had the properties of both a wave and a particle.

Later the reverse argument came to be applied to the electron. Summing up investigations into the behaviour of electrons, Sir James Jeans stated that: 'The hard sphere has always a definite position in space; the electron apparently has not. A hard sphere takes up a very definite amount of room; an electron – well, it is probably as meaningless to discuss how much room an electron takes up as it is to discuss how much room a fear, an anxiety, or an uncertainty takes up.'

In 1925 a young Frenchman called Louis-Victor de Broglie suggested that electrons could usefully be regarded as waves. Experimental evidence was soon forthcoming to back up his suggestion, for it was discovered that a beam of electrons when passed through a metal crystal produced wave diffraction patterns similar to those of light. The question whether an electron is a wave or a particle is not one that we know how to answer: it has properties of both. Nevertheless it is often desirable to have a visual picture of the electron, and for practical purposes one of the most useful pictures is that of a 'cloud' of negative charge in which the charge is likely to be more dense in some areas than in others. (De Broglie's wave theory of the electron is outlined in the Background Book, *The Way of Discovery*.)

Part three The atomic nucleus

H. G. J. Moseley (1887–1915) showed that the properties of a chemical element are determined largely by its atomic number or number of units of positive charge in its atomic nucleus.
The Royal Society

Atomic number – In Rutherford's model of the atom (and, indeed, in our present-day model), the mass of the atom is concentrated in the nucleus – the mass of the electrons, as we saw, is almost negligible. Also, all the positive charge is concentrated in the nucleus.

In 1913 a young English physicist called Moseley was investigating the X-ray spectra of certain elements (see the Background Book, *The Start of X-ray Analysis*). From his results, he found that the atomic nucleus of each element had a characteristic positive charge. He called this its atomic number. Thus hydrogen had a positive charge of 1 (and therefore 1 electron to balance it), helium had a positive charge of 2 (and therefore 2 electrons), lithium had a positive charge of 3 (and therefore 3 electrons). He also found that, if the elements were arranged in order of their atomic numbers, their sequence was *almost* identical with that when they were arranged in order of their atomic weights. It was *almost* identical but not quite – a few elements did not fit. These few elements had been the misfits in Mendeleev's original periodic table. Moseley's work showed that a periodic table based on atomic number, instead of atomic weight, produced

Frederick Soddy (1877 – 1956) who was associated with Rutherford in the theory of disintegration of radioactive elements and who suggested the possible existence of isotopes.

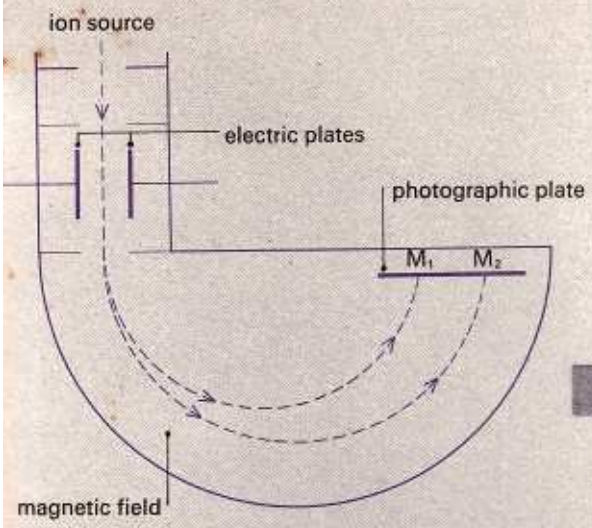
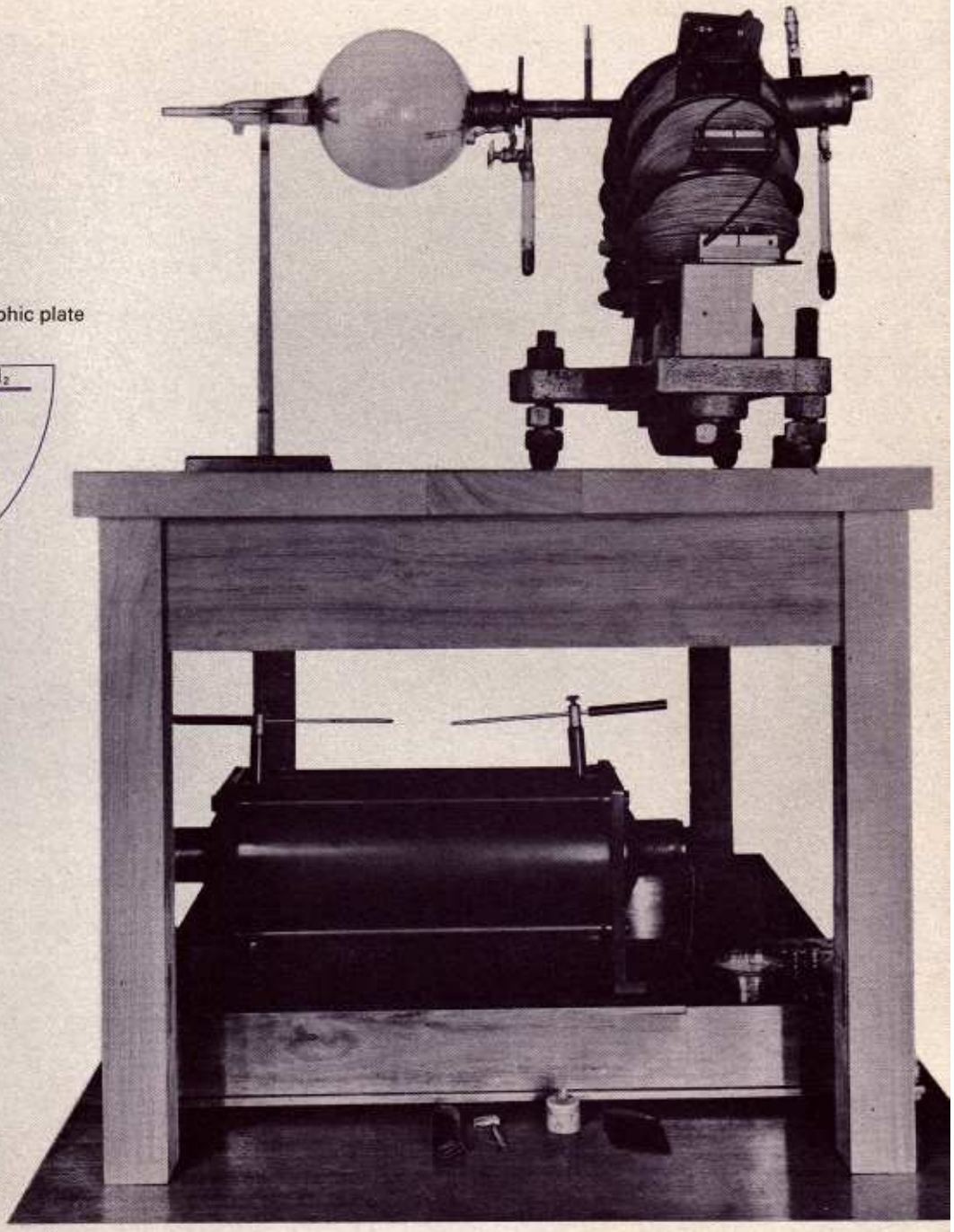


Diagram of mass spectrograph – A beam of positively-charged ions is deflected by a magnetic field. The extent of deflection (recorded on a photographic plate) depends on the masses of the individual ions; hence isotopes of differing mass (M_1 and M_2) show as separate regions on the plate. By using an electric field in conjunction with the magnetic field the deflection of the ions is made independent of their velocity.



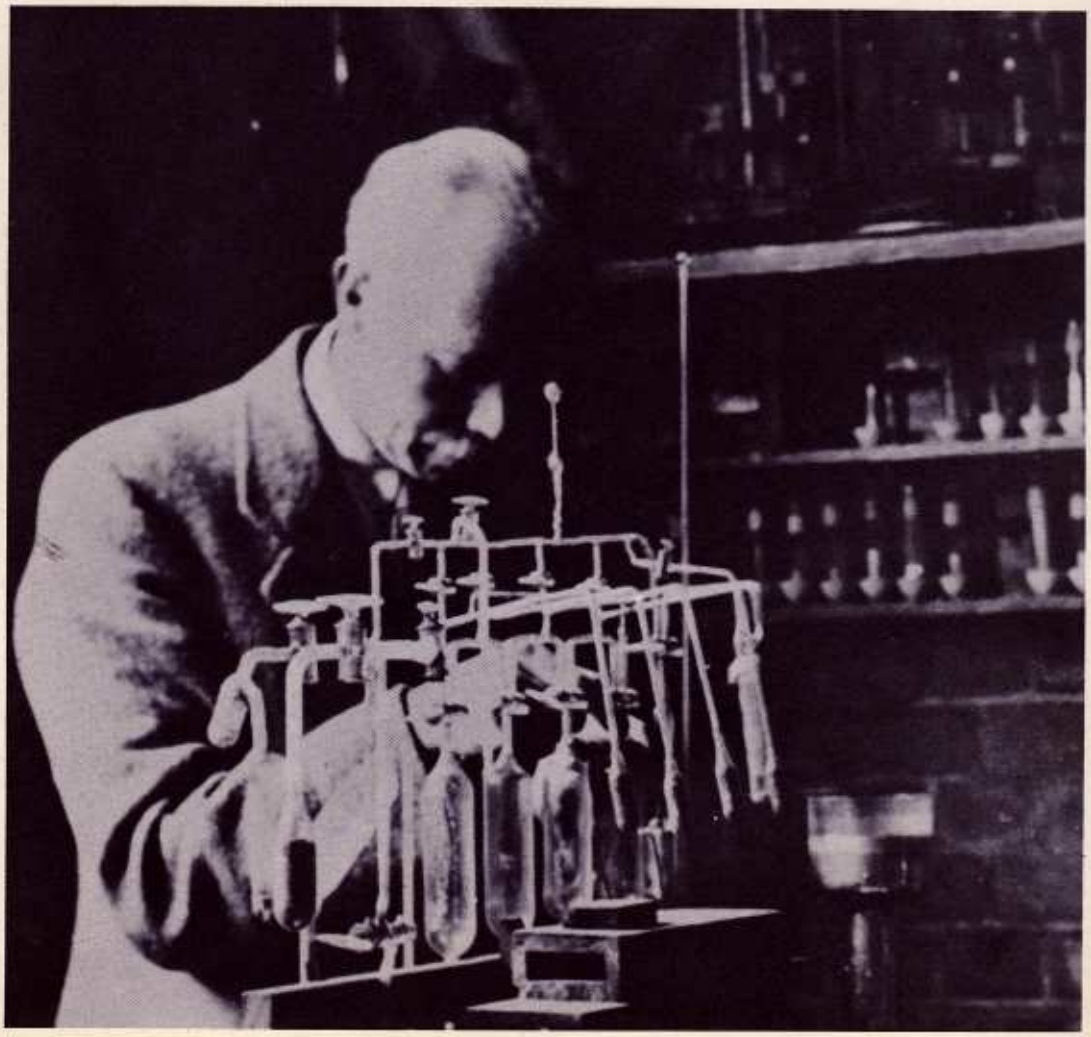
Aston's mass spectrograph. *Crown Copyright. Science Museum, London*

a more logical arrangement. Atomic number was found to be more fundamental than atomic weight in determining the chemical properties of an element.

Isotopes – When a lot of people become interested in a particular area of scientific investigation, it often happens that the findings branch out in a number of directions. So it was with investigations into the structure of the atom.

As long ago as 1886, the same Sir William Crookes who discovered the electrical nature of cathode rays suggested: 'When we say the atomic weight of, for instance, calcium is 40, we really express the fact that, while the majority of atoms have an actual weight of 40, there are not a few which are represented by 39 or 41, a less number by 38 or 42, and so on.' In other words, he was saying that atoms of the same element were not identical in weight, thus contradicting the views of Dalton.

As a result of his earlier work on radioactivity, Frederick Soddy came out in 1913 even more forcibly with the same view. For atoms of the same element, therefore with the same



F. W. Aston (1877 – 1945), whose mass spectrograph enabled the masses of individual atoms to be investigated and so led to the experimental discovery of isotopes. *Cavendish Laboratory Cambridge*

chemical properties, but of differing atomic weight, he coined the word 'isotope'. This is from the Greek 'isos' meaning equal, and 'topos' meaning place; it refers to the 'equal place' of the atoms in the periodic table.

For some years there was little experimental evidence to support Soddy's idea of isotopes. Then in 1919 F. W. Aston investigated the masses of individual atoms with an instrument called a mass spectrograph. This instrument works on the principle of passing charged atoms through an electric field and it showed that Soddy's prophecy was correct. It was found that the atoms of practically all elements had isotopic forms. Thus chlorine, with an atomic weight of 35·457, was shown to consist of a mixture of atoms of mass 35 and of mass 37 – 35·457 represents the *average* weight of many millions of atoms. The masses of individual atoms were found to be very nearly whole number ratios – as in the example of chlorine above, not 35·457 but very nearly 35 or very nearly 37.

The atomic nucleus – The idea of atomic number and the discovery of isotopes led to great simplifications in the interpretation of atomic structure. But, oddly enough, the kind of interpretation arrived at had been foreseen over a hundred years previously by an English physician called Prout. Prout had put forward the idea that the atoms of all elements were built up from hydrogen atoms, but his idea was eventually rejected because some atomic weights were found to contain fractions. We now know, following the discovery of isotopes, that this objection was no longer valid.

For practical purposes, we may regard the hydrogen nucleus, called a proton, as having an atomic mass of 1. Thus, since isotopes show that the atomic masses of all atoms are very nearly whole numbers, we could perhaps think of the nuclei of all atoms as being built up of protons. But each proton carries a single positive charge and if atoms were built up solely of protons, their atomic numbers would be the same as their atomic weights. This is not so; for example the atomic weight of oxygen is 16 but it only has an atomic number of 8 (or 8 positive charges). What makes up the difference? This problem was resolved with the discovery by Sir James Chadwick (in 1932, at the Cambridge Cavendish Laboratory) of a nuclear particle with a mass similar to that of the proton but with no electrical charge. It was named the neutron. At last, it seemed, the structure of the atomic nucleus was clear: it was built of positively-charged protons and electrically-neutral neutrons. Thus the oxygen nucleus consists of 8 protons (atomic number 8) plus eight neutrons (atomic mass 16). Or the gold nucleus consists of 79 protons (atomic number 79) plus 118 neutrons (atomic mass 197). The structure also explained isotopes. Thus all chlorine nuclei have 17 protons (atomic number 17) but some have 18 neutrons (atomic mass 35) and others have 20 neutrons (atomic mass 37).

As a result of further investigations we now believe this picture of the nucleus to be oversimplified. In their search to explain nuclear properties, scientists have come across numbers of other nuclear particles in addition to the proton and the neutron. But the picture is a complicated one, and there is no point in probing it further here.

Sir James Chadwick (born 1891) discovered the neutron.
Camera Press

Part four Energy from the atom

Cloud chamber photograph showing the collision between a nitrogen atom and an α particle. The α particle has been bounced off at an angle of about 120°, and the nitrogen atom has been transmuted into an oxygen atom.
Science Museum, London. By courtesy of Professor P. M. S. Blackett, F.R.S.

Changing one element into another – It had been the dream of the alchemists to transmute 'base' metals into gold. They failed. But, with a new insight into the structure of the atom, transmutations of this kind eventually became possible.

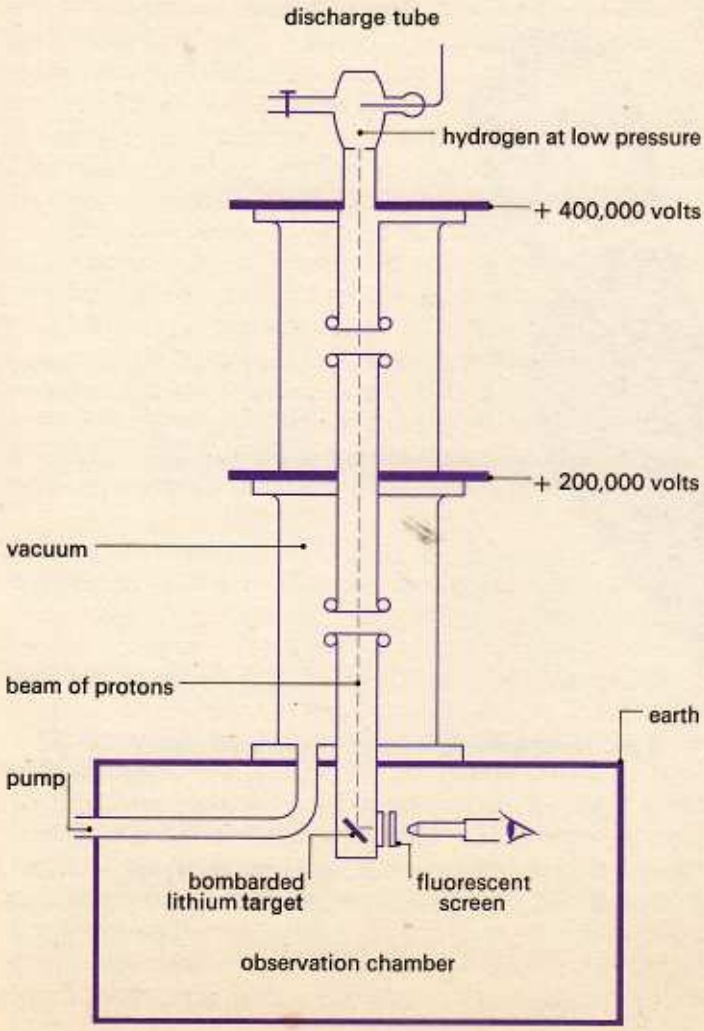
Radioactivity is itself a kind of natural transmutation in which the radioactive elements lose protons and electrons to become other elements. The first artificial transmutation was carried out by Lord Rutherford in 1919. Using a radioactive source, he bombarded nitrogen gas with helium nuclei (α particles), and, by dislodging a proton, managed to convert a few of the nitrogen atoms into oxygen. How can we represent transmutations of this kind in the form of an equation? In representing the transmutation of one element into another, we are concerned not so much with the number of atoms (as in conventional equations) as with the nuclear structure of the individual atoms. We want to know how many protons each atomic nucleus contains (atomic number) and how many protons plus neutrons (atomic mass). Therefore, we write the atomic mass at the top and the atomic number at the base of each chemical symbol. For example, $^{17}_{8}O$ is an oxygen isotope containing 8 protons and 9 neutrons, and $^{4}_{2}He$ is a helium nucleus (α particle) containing 2 protons and 2 neutrons. In presenting the transmutation, we must see that the number of protons and neutrons on the left of the equation balances the number of protons and neutrons on the right. Thus, in Rutherford's experiment:

$$\underset{\text{nitrogen nucleus}}{^{14}_{7}N} + \underset{\text{particle}}{^{4}_{2}He} \rightarrow \underset{\text{oxygen isotope}}{^{17}_{8}O} + \underset{\text{proton}}{^{1}_{1}H}$$

Subsequently, Rutherford and Chadwick carried out similar transmutations among many others of the lighter elements.

To bring about nuclear transmutations, the projectile particles must have very high energies. Rutherford had done it

Diagram of the apparatus built by Cockcroft and Walton for bombarding lithium with protons.



Sir John Cockcroft in the Cambridge Cavendish Laboratory at the time of his famous experiment – the first nuclear transmutation using artificially-accelerated projectiles. In collaboration with Walton, he bombarded lithium with protons and thereby converted some of it into helium.
Keystone

Albert Einstein (1879 – 1955), whose theoretical equation relating mass and energy preceded the experimental conversion of mass into energy by over a quarter of a century. *dpa-Bild*

using α particles from a radioactive source but in 1932 Sir John Cockcroft and Dr E. T. Walton, working in Rutherford's laboratory in Cambridge, used artificial projectiles instead of natural ones. They were able to produce projectiles of sufficient energy by ionizing hydrogen gas and accelerating the hydrogen ions (protons) so formed in a high-voltage electric apparatus. With these high-speed protons, they bombarded the element lithium and converted some of it into helium (or α particles). (See Background Book, *The Way of Discovery*.)

Thus:

$$\underset{\text{lithium nucleus}}{{}^{7}_{3}\text{Li}} + {}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + \underset{\text{two } \alpha \text{ particles}}{{}^{4}_{2}\text{He}}$$

In this reaction, a very large amount of energy is released. The explanation for this was to be found in Einstein's famous equation, published over twenty-five years before, that $E = mc^2$, where E = energy, m = mass, c = the velocity of light. This equation shows that a small amount of mass can be converted into a large amount of energy. In the transmutation of lithium into helium, the combined mass of the two helium atoms is slightly less than the combined mass of the lithium atom and the proton. The large release of energy in the transmutation of lithium into helium is explained by this loss of mass, and the experiment of Cockcroft and Walton provided what was then the best experimental proof of Einstein's equation. As we shall see shortly, further and more dramatic proof was soon to come.

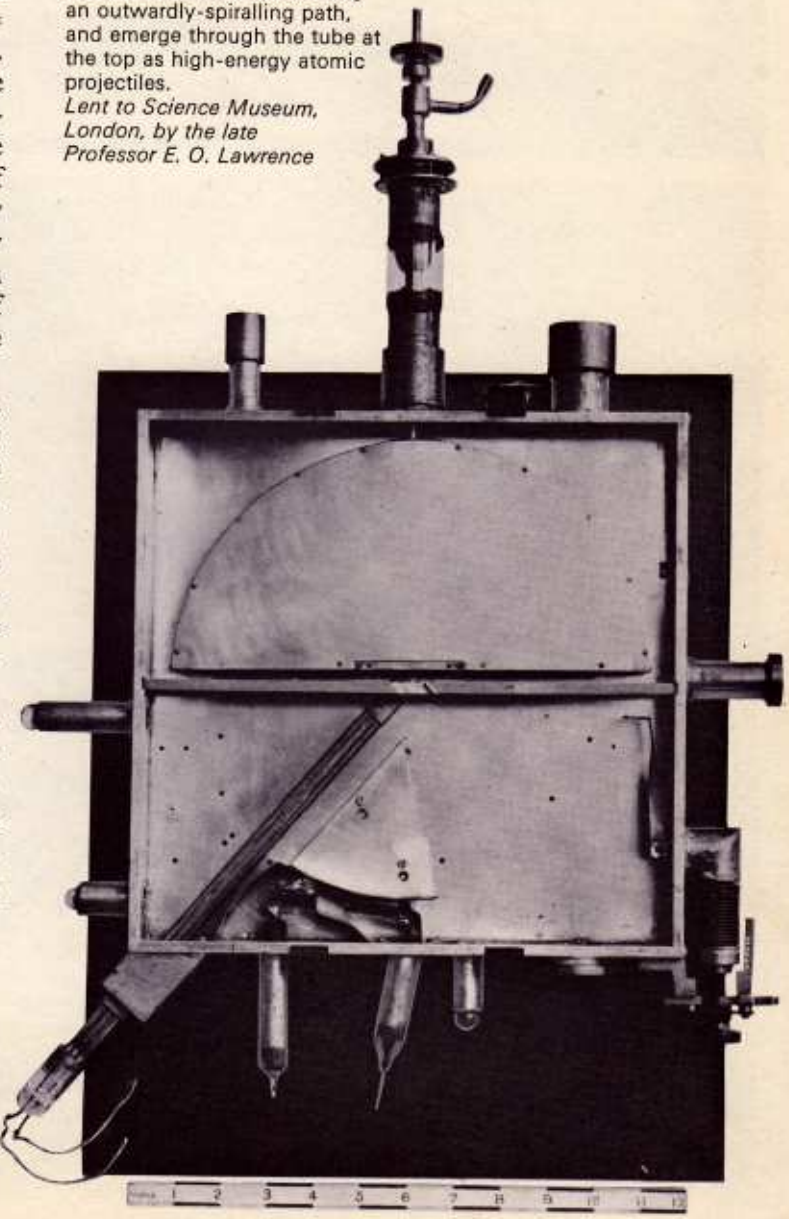
At about the time of Cockcroft and Walton's experiments, other machines able to accelerate electrically-charged particles were coming into being. Perhaps the best known of these machines was the cyclotron, invented by the American E. O. Lawrence whose name is remembered in the man-made element Lawrencium (atomic number 103). These machines are now able to produce atomic projectiles with very high energies indeed, and have led to one of the most fascinating of the recent advances in chemistry – the making of new elements.

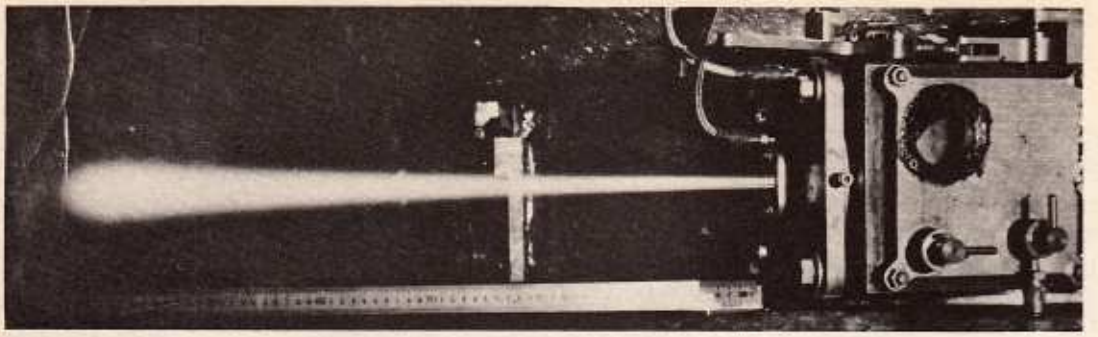
Building up elements – The first transmutations involved breaking down heavier elements into lighter elements. Obviously the reverse process – building up lighter elements into heavier ones – soon began to interest scientists. The first scientists to achieve this (in 1934) were Irene Joliot-Curie, a daughter of Madame Curie, and her husband Frederick Joliot. They converted some aluminium into phosphorus by bombarding the aluminium with α particles.
Thus:

$${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow {}^{30}_{15}\text{P} + {}^{1}_{0}\text{neutron}$$

The heaviest natural element is uranium with an atomic number of 92 and an atomic mass of 238. In 1940 American chemists working at Berkeley in California began building up new elements starting from uranium. Using a cyclotron they have, to date, made eleven. All the elements are radioactive and most of them break down very rapidly. Also it is

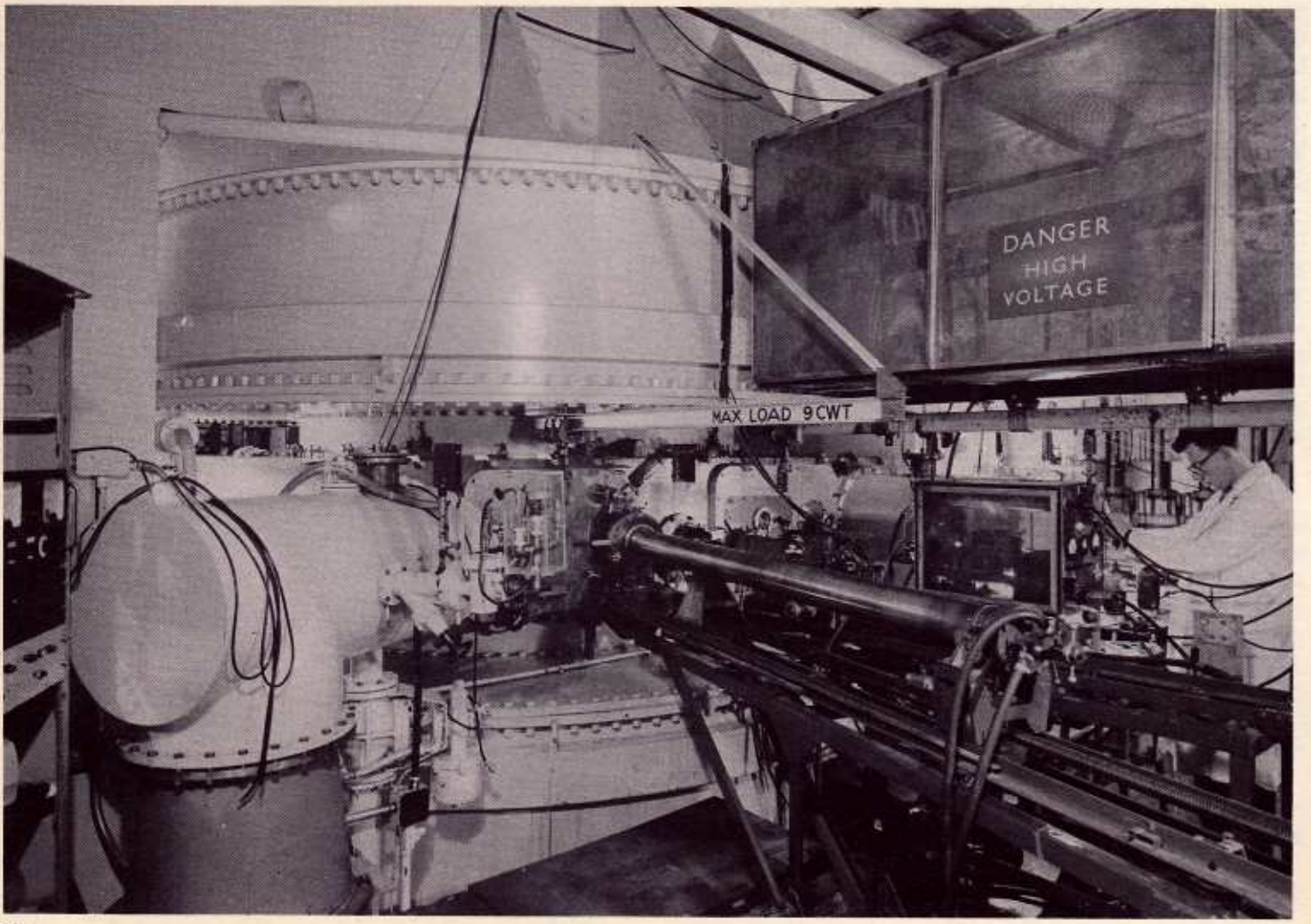
One of the first cyclotrons – designed by Lawrence and Livingston. Charged atomic particles enter the cyclotron through the tube, bottom left. The particles are accelerated by a series of voltage kicks along an outwardly-spiralling path, and emerge through the tube at the top as high-energy atomic projectiles.
Lent to Science Museum, London, by the late Professor E. O. Lawrence





A beam of high-speed deuterons (heavy hydrogen nuclei) emerging from a cyclotron installed at Berkeley, California.

A modern cyclotron at the Atomic Energy Research Establishment at Harwell. The accelerating chamber is in the background.
U.K. Atomic Energy Authority



possible to produce most of them only in small quantities – sometimes only millionths of a gram – and their identification requires extremely delicate analysis. The kind of reactions involved in making, say, neptunium (atomic number 93) and plutonium (atomic number 94) are:

$$^{238}_{92}\text{U} + {}^{1}_{0}\text{neutron} \rightarrow {}^{239}_{92}\text{U} + \gamma\text{ray} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{electron}$$

Neptunium rapidly decays as follows:

$$^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{electron}$$

Of the many people who have collaborated in this work, Dr E. M. McMillan and Dr G. T. Seaborg are perhaps the best known. (See Background Book, *The Way of Discovery*.)

Atomic energy – We saw earlier an example of mass being converted into energy, but at the time, the changing of a few lithium atoms into a few helium atoms provided little insight into what was in store. How atomic energy could be harnessed on a large scale was discovered almost by chance. Shortly before the Second World War, several European scientists – in particular Otto Hahn and his colleagues in Germany – were attempting to build up a new series of elements by bombarding uranium with neutrons. As we have seen, the making of new elements was later successfully accomplished by the Americans, but these first experiments did not go according to plan. Instead of building up into a new element, the heavy uranium nucleus split in half to form two very much lighter elements (see diagram). This conversion involved a substantial loss of mass and hence a large release of energy; but, even more significant, the uranium nucleus, when it broke down, released more neutrons. These neutrons, in turn, were able to break down more uranium nuclei and so on, leading to a chain-reaction with an immense release of energy. It was subsequently discovered that it was not uranium with an atomic mass of 238 that underwent this fission reaction but a much rarer isotope with an atomic mass of 235. However, uranium 238 can be converted fairly readily into plutonium (see the equations above), and this element behaves in much the same way as uranium 235. You have, perhaps, heard of a 'breeder' reactor: it is in a reactor of this kind that the conversion from uranium 238 to plutonium is made. These then are the principal atomic fuels – uranium 235 and plutonium.

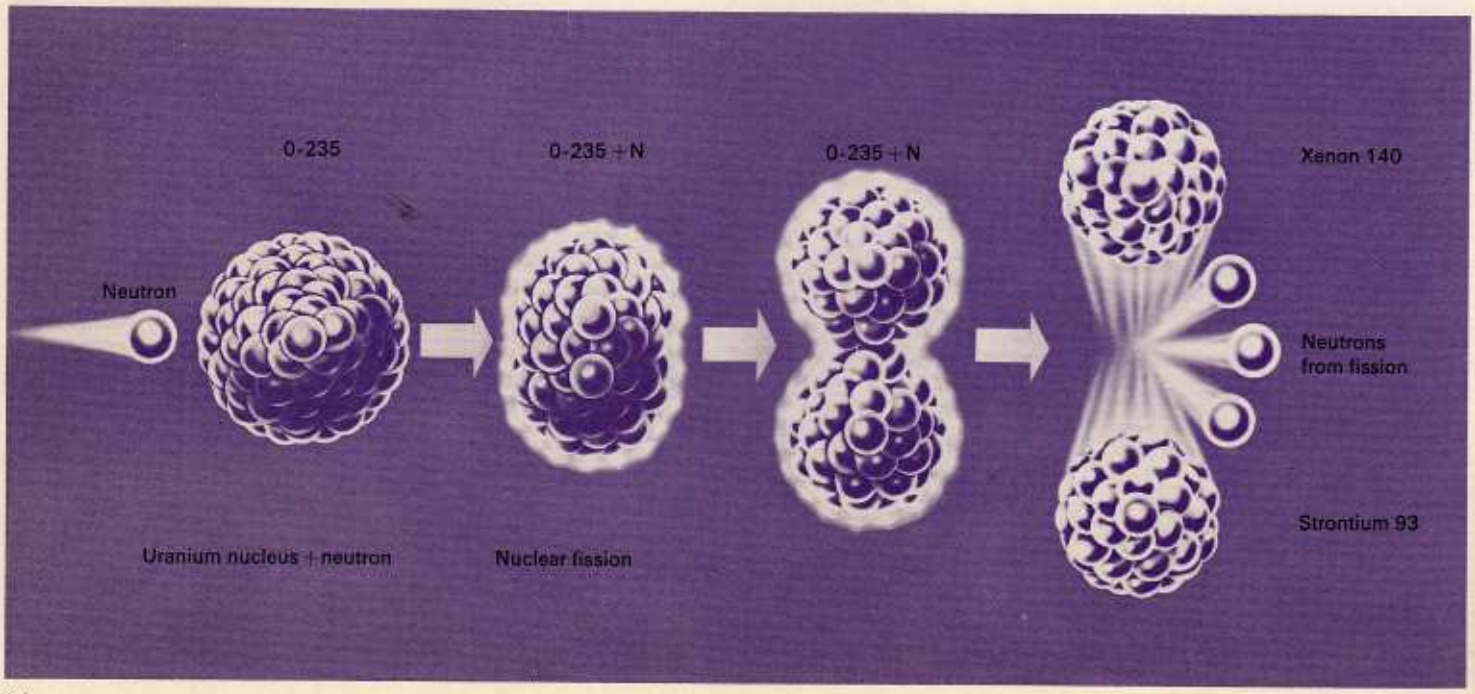
As you will know, atomic energy can be used in two very different ways. In complicated equipment called an atomic

Frederick Joliot (1900 – 1958) and Irene Joliot-Curie (1897 – 1956), the first to build up heavier elements from lighter elements.
E. Wehner

A historic photograph – the first sample of a plutonium compound (2·77 micrograms of oxide) to be weighed by man. The plutonium compound shows as a crusty deposit (indicated by the arrow) on the platinum weighing boat. The weighing boat is gripped on the right by a pair of forceps.

Glenn Seaborg (born 1912) has, with his research team, built up several new elements from uranium. He is in the laboratory where much of the early work was done on making plutonium.

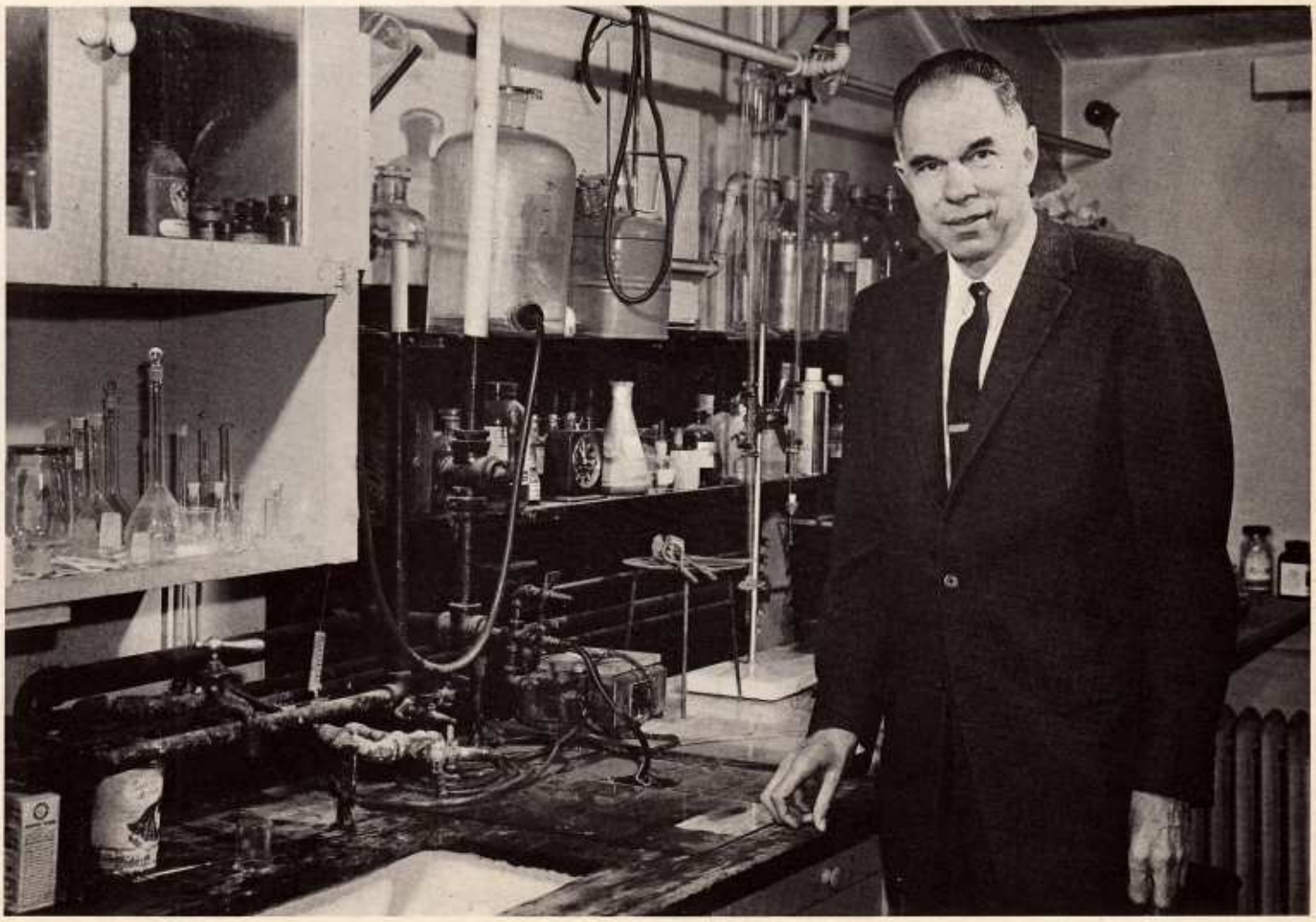
Diagram showing the fission of a uranium nucleus when struck by a neutron. Note that it is the nucleus (without electrons) and not the atom which is shown. Note also that the fission products include more neutrons, thereby generating a chain reaction.
U.K. Atomic Energy Authority



pile, the fission chain-reaction is carefully controlled by slowing it down, and the nuclear energy can be 'tapped' from the pile and converted into electricity or other useful energy forms. In an atomic bomb, the fission reaction proceeds in an uncontrolled manner, and the destructive energy release is enormous. Also, the uranium nuclei break down into highly radioactive elements which greatly add to the devastation.

The fact that atomic energy came into prominence at the start of the war meant that the first efforts of scientists were devoted to making use of its destructive power. The story began with a letter from Albert Einstein to Franklin D. Roosevelt, the American President, in August 1939:

'In the course of the last four months it has been made probable through the work of Joliot in France as well as Fermi and Szilard in America – that it may become possible to set up a nuclear chain-reaction in a large mass of uranium by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.



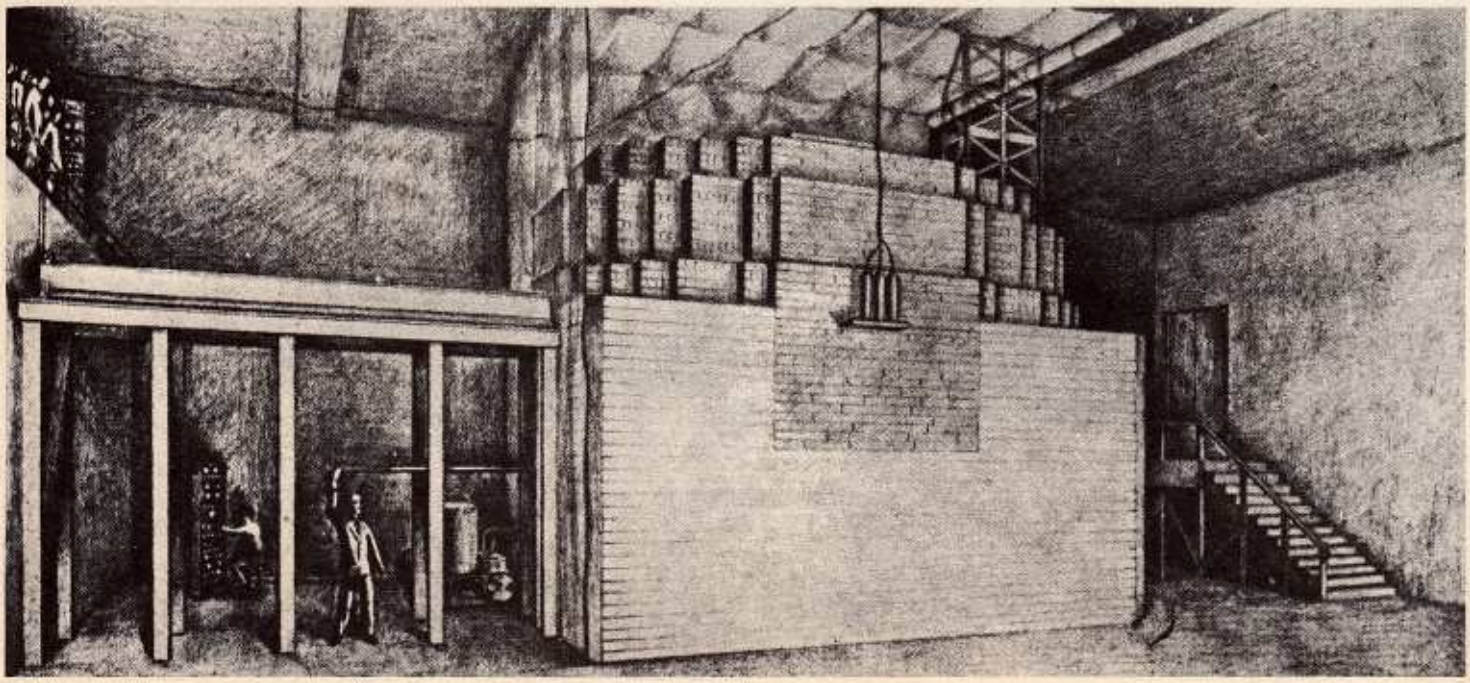
Enrico Fermi (1901 – 1954) built the first nuclear reactor.
U.S. Army Signal Corps

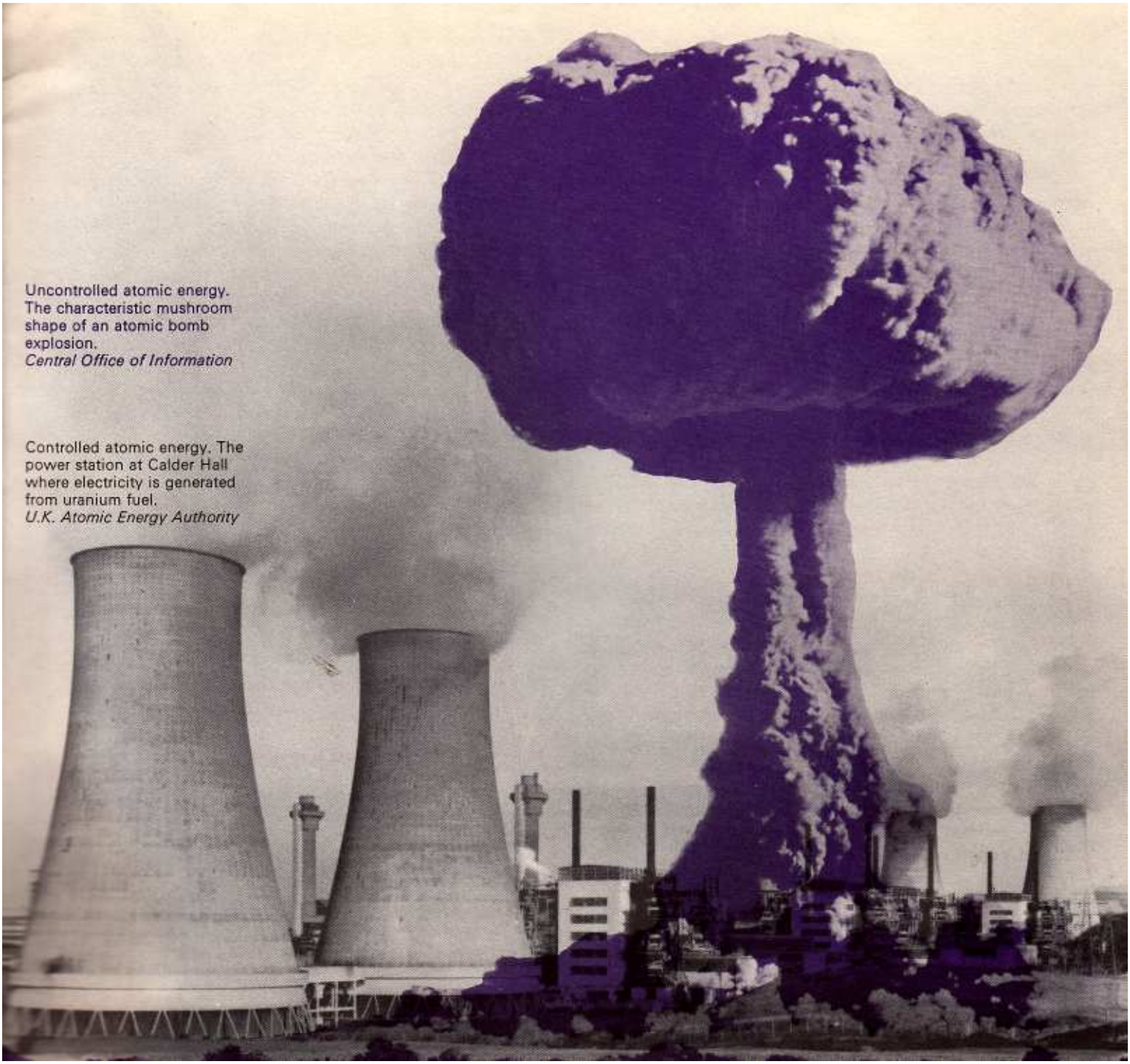
Sketch of Fermi's nuclear reactor built in a Chicago squash court. The uranium fuel and the graphite for moderating the chain reaction were built up into a great pile, since when the nuclear reactors have been commonly called atomic piles.
U.S. Army Signal Corps

'This new phenomenon would also lead to the construction of bombs, and it is conceivable – though much less certain – that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.'

The first nuclear chain-reacting pile, built by the brilliant Italian scientist Enrico Fermi in a Chicago squash court, began working in 1942. The story culminated in the dropping of two atomic bombs on the Japanese cities of Hiroshima and Nagasaki in August 1945.

After the war people confidently expected that atomic fission would bring to the world vast quantities of energy at practically no cost. This dream has not come true. But, although it has so far been less easy than expected to harness the energy of the atom, power stations operating on atomic fuel are in operation in many parts of the world, and it is fairly certain that atomic energy will be increasingly used in the future.





Uncontrolled atomic energy. The characteristic mushroom shape of an atomic bomb explosion.
Central Office of Information

Controlled atomic energy. The power station at Calder Hall where electricity is generated from uranium fuel.
U.K. Atomic Energy Authority

One other source of this energy that we have not yet mentioned is fusion. Two nuclei of deuterium (an isotope of hydrogen containing a neutron as well as a proton) can, in extreme temperature conditions, be made to fuse to form a helium atom. In this fusion reaction, the loss of mass and the energy of release are very much greater than in the conventional fission reaction – as witness the sun which produces its energy in this way. You may wonder how it is that with some atoms fusion results in a loss of mass and that with other atoms the opposite process of fission results in a similar loss. Generally, loss of mass results from fusion between lighter nuclei (that is, with an atomic mass less than about 40 – for example, hydrogen) and from fission of heavier nuclei (with an atomic mass greater than 40 – for example, uranium). The explanation for this is not a simple one. It lies in the balance between the electrical forces acting on the nuclear particles and on the surface forces holding the particles together. In lighter nuclei, the surface forces predominate, but in heavier nuclei the electrical forces become increasingly important. So far it has proved impossible to control the fusion reaction, and its use has been restricted to the hydrogen bomb. However, it should only be a matter of a few years before this reaction, too, is brought under control.

The atomic models – As we have seen, many famous scientists have contributed to our understanding of the atom. Some have been physicists, others chemists, because here, in finding out the structure of the atom, both physicists and chemists have a mutual interest. Sometimes the discoveries have come about through planned investigation, for example, the making of new elements by the Americans. Sometimes they have come about by chance, for example, Becquerel's discovery of radioactivity and the discovery of uranium fission. Sometimes they have even been predicted beforehand, for example, Soddy's prophecy about isotopes and Einstein's equation predicting the conversion of mass into energy.

It is, of course, only those discoveries and ideas which have ultimately proved useful that we hear about. Much work was done that, in the end, led nowhere. At the time it is often difficult to assess the value of a discovery or an idea. It is only on looking back that we are able properly to judge and to link up the discoveries into the coherent pattern that we have here. As a pattern it is far from complete, and many of our best scientists are still working hard to reveal more of the mysteries of the atom.

In this brief survey we have seen that ideas about the atom have changed many times. But, essentially, these ideas can be reduced to five basic models: Dalton's solid atom; Rutherford's 'solar-system' atom; the atom of the late 'twenties in which the wave properties of the electron were incorporated; the atom of the early 'thirties in which the nucleus was built up of protons and neutrons; and the present-day model in which the nucleus contains, as well as neutrons and protons, many other kinds of particle. As to future models, who knows?

These models represent the development of many ideas, each new model being a refinement of the one before, usually more complicated but able to explain a wider range of experimental phenomena. As pointed out at the beginning, we do not necessarily drop the old model in favour of the new. In our study of chemistry, we use the simplest model that is able to help us with the kind of problems we are tackling. Sometimes this may be Dalton's model. At other times, it may be the present-day model.

Questions

1. Knowing that the mass of an electron is only about 1/1800 of the mass of a hydrogen atom, is it safe to assume that an electron is smaller than a hydrogen atom?

2. At a pressure of about $\frac{1}{2}$mm of mercury, a glow begins to appear in a vacuum tube. How much less than atmospheric pressure is this?

3. In Einstein's equation, $E=mc^2$, what is there to suggest that a small loss of mass will produce a large quantity of energy?

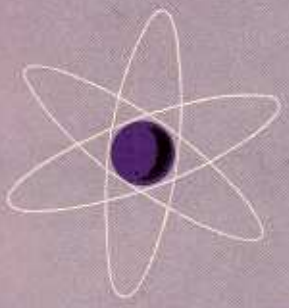
4. Why was Rutherford so surprised when some of the α particles bounced back from the gold foil?

5. List the names of the eleven elements that are heavier than uranium.

6. Write an equation for the bombardment of a beryllium nucleus ($^{9}_{4}Be$) by an α particle. The main conversion product is carbon ($^{12}_{6}C$).

Some atomic models

1804
Dalton's solid atom.



1913
The Bohr-Rutherford 'solar-system' atom in which electron 'planets' orbit round a nuclear 'sun'.

1924
The de Broglie atom in which the electron is no longer treated as a particle.

1932
The atom in which the nucleus is built up from neutrons as well as protons.

1966
The present-day atom in which the nucleus is built up from many kinds of particles.

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