Advanced Level Atomic Physics

G. M. Mossop, M.A.
Head of Physics Department, Sutton High School

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List of Plates

structure of the aluminium atom? (For arrangement of electrons see Chapter 11.)

A solid aluminium sphere has a radius r of 10 cm. Find: (*a*) the total number of electrons in the sphere and (*b*) the fraction of these which are removed when the sphere is raised to a positive potential of 100 volts. (Avogadro's number $= 6{\cdot}0 \times 10^{23}$ atoms per gram-atom. Density of aluminum $= 2{\cdot}7$ gm. cm^{-3}. Electronic charge $= -4{\cdot}8 \times 10^{10}$ e.s.u; 1 e.s.u. of potential $=$ 300 volts.) (Note capacity $= r = 10$ e.s.u. and charge = capacity $\times$ potential.) N 60 II–7

4. The electrochemical equivalent of copper is 0·00033 g per coulomb, its atomic weight is 64 and its valency is 2. Find the number of electrons required to neutralise 64 g of Cu^{++} and hence evaluate Avogadro's number. (Charge on an electron $= -1{\cdot}6 \times 10^{-19}$ coulomb.)

Chapter Two

Electrons and Cathode Rays

Electrons are the most accessible of the sub-atomic particles because they form the outer layers of atoms, and since they are fairly easy to remove they can be studied when isolated or when constituting part of an atom. Electrons are responsible for many properties of materials such as electrical conduction, magnetism, and the type of spectra emitted; they are also responsible for chemical properties which can be accounted for by the arrangement of the outermost electrons in the atoms since this determines the manner in which one atom can combine with another. Electrons, therefore, play a very important part in the behaviour of different elements, and we shall be discussing their rôle in the atom later in this book. In this chapter we shall confine our attention to the properties of the electrons themselves.

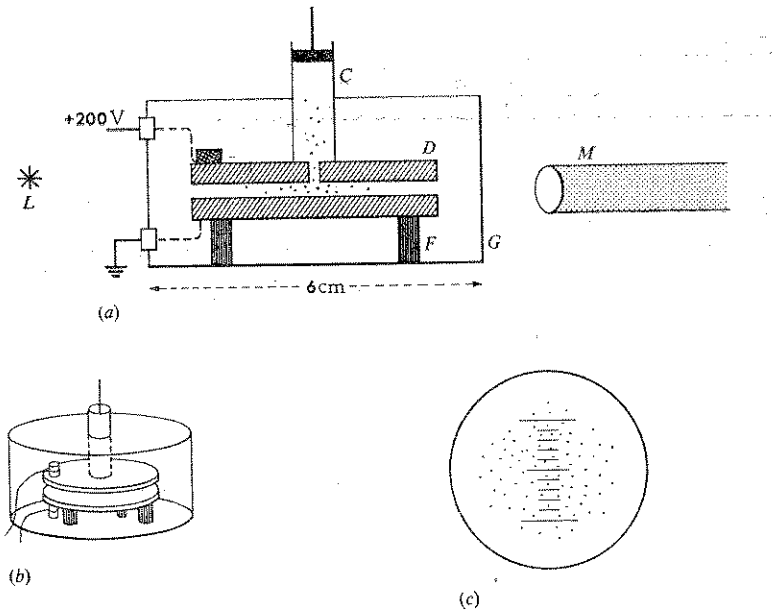
1 Millikan's oil drop experiment and the determination of electronic charge, *e*

Electric charge, like matter, is either particulate or continuous. A number of experiments were undertaken to obtain evidence for its particulate nature, of which the most celebrated is probably that first carried out by Millikan in 1909. His experiment also enabled the magnitude of the basic unit of charge to be deduced; it is assumed that this basic unit is the charge of an electron, which was the name originally given to the particle which constitutes part of an atom.

A modern form of Millikan's apparatus is shown in Fig. 2. A small drop of oil is viewed in the gap between a pair of horizontal metal plates D across which an electric field can be applied. (Oil is used because its low rate of evaporation ensures that the radius of a drop remains unchanged over a long period.) The plates are separated by about $\frac{1}{2}$ centimetre and are surrounded by a case G, for protection against draughts and temperature fluctuations. The region between the plates is illuminated, and individual drops may be viewed using a long focus microscope M which carries a scale in the eyepiece.

To demonstrate the particulate nature of electric charge (simple method)

A fine mist of oil is forced into a hollow cylinder C above the upper plate by means of a sprayer like a scent spray and some of the drops find their



C, cylinder into which oil is sprayed; D, brass disc with fine central hole; F, insulating feet; G, protecting case; L, light source illuminating droplets; M, microscope.

Fig. 2 Millikan's oil drop experiment for demonstrating the particulate nature of electricity and measuring e
(a) *Plan*
(b) *Perspective*
(c) *Field of view in microscope*

way through a small hole into the gap between the plates. The action of the sprayer causes many of the drops to become charged either positively or negatively; this charge may eventually get lost, or additional charge may be gained by the impact of charged ions of air.

A positive potential of a few hundred volts is applied to the top plate while the bottom plate is earthed, so that drops carrying a negative charge are attracted upwards; a suitable drop is selected and the applied voltage V_1 is adjusted until this drop remains stationary at a mark on the scale. The upward force acting on it due to the electrical attraction (equal to field × charge) must then exactly balance its weight,

$$\text{hence } X_1 q_1 = W,$$

where W is the weight of the drop, q_1 is its negative charge, and the field

X_1 = potential gradient $= \frac{V_1}{d}$, d being the separation between the plates.

It is found that the drop remains stationary for some time after the potential has been adjusted and then it may suddenly begin to move. Since its weight remains constant, the movement must be the result of a change in charge q. The potential is again adjusted to make the drop float without moving, so that $X_2 q_2 = W$, and therefore $q_2 = \frac{W}{X_2}$.

The change in charge is then given by

$$q_2 - q_1 = \frac{W}{X_2} - \frac{W}{X_1} = \frac{W}{V_2/d} - \frac{W}{V_1/d} = Wd\left(\frac{1}{V_2} - \frac{1}{V_1}\right),$$

i.e. the change in charge is proportional to $\frac{1}{V_2} - \frac{1}{V_1}$.

It is found that the change is always abrupt, and this means that the charge does not leak away gradually but is lost by discrete amounts; furthermore, if one drop is viewed over a considerable period of time the changes nearly always have the same numerical value, but occasionally they have double or treble this value. This provides strong evidence in support of the particulate nature of electricity. It is assumed that the basic particle of charge is an electron, which implies that static charge is due to an excess or deficiency of electrons.

This method of balancing the electrical force against the weight does not, however, enable the magnitude of the changes in charge to be determined, since the weight W of the drop is not known, and hence a different technique must be used if the magnitude of the charge is required.

To evaluate the electronic charge

In order to find the magnitude of the basic unit of charge it is necessary to measure the forces acting on a drop. This can be done by utilising a relation known as Stokes Law, from which it can be shown that a small drop of radius a falling through air will almost immediately acquire a steady *terminal velocity*, u, whose magnitude is proportional to the accelerating forces. In this experiment the accelerating forces are the electrical attraction on the drop acting upwards, and its weight W acting downwards;

hence $$Xq - W = Ku \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where K is an unknown constant. Thus the forces can be determined by measuring the velocity u if K can be found. In order to evaluate K the velocity u_0 is measured when the field is switched off and the drop is falling downwards under the influence of gravity alone. Then $W = Ku_0$, and this

enables the radius of the drop to be determined and thence W and K can be evaluated. (For details of this, see section **2** below.)

The experiment consists of applying a potential difference V between the plates, which is large enough to make some drops rise, and then selecting a suitable drop and measuring its velocity u_1 by timing its passage across a known section of the scale in the eyepiece of the microscope. The supply voltage is then switched off and the downward velocity under the action of gravity is measured. The potential difference of the supply is kept constant and it is switched on and off alternately: in this way a single drop can be observed for half an hour. When the field is on, occasional abrupt changes in the velocity will indicate that the charge on the drop has changed abruptly and from equation (1) above.

$$X(q_2 - q_1) = K(u_2 - u_1) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Hence the particulate nature of electric charge can be verified by observing that the change in velocity $(u_2 - u_1)$ nearly always has the same numerical value, but occasionally double or treble this value. This is an alternative method to that described above.

By substituting for the values of K and X in equation (2), the magnitude of the change in charge is always found to be a small integral multiple of $1{\cdot}602 \times 10^{-19}$ coulomb, so that this must be the magnitude of the charge of an electron. The value of the electronic charge which Millikan thus found agreed, within the limits of experimental error, with the charge that can be associated with a monovalent ion in electrolysis. This experiment therefore supports the view that charges on ions are due to the gain or loss of electrons. (See Questions 1 and 2 at the end of the chapter.)

*2 Detailed theory of Millikan's experiment

Any small oil drop falling through air will experience a force opposing the motion on account of the viscosity† of the air, and the magnitude of the force increases with the velocity of the drop. This force of viscosity will therefore increase as the drop accelerates until it is equal and opposite to the forces causing the acceleration, and then no further acceleration will take place so that the drop moves with a steady velocity. The maximum velocity acquired by the drop is called its terminal velocity, u; the corresponding viscous force F is given by Stokes Law which states that $F = 6\pi\eta au$, where a is the radius of the oil drop and η (eta) is the coefficient of viscosity, which can be found from tables.

When a potential of $+V$ is applied to the upper plate relative to the lower one, producing an electric field $X = \frac{V}{d}$, then the viscous force F

* Sections asterisked may be omitted. † See glossary.

opposing the upward motion when the terminal velocity has been reached is $Xq - W$.

$$\text{Hence } Xq - \tfrac{4}{3}\pi a^3\rho g = F = 6\pi\eta a u_1$$

where u_1 is the terminal velocity upwards and ρ is the density of oil. Thus the constant K in equations (1) and (2) of the preceding sections is given by $K = 6\pi\eta a$.

In order to evaluate K the field is switched off and the drop moves downwards with a terminal velocity u_0.

$$\text{Then } \tfrac{4}{3}\pi a^3\rho g = 6\pi\eta a u_0$$

and from this the radius a can be determined and hence a numerical value can be given to the constant K. By substituting this value in the relation

$$\frac{V}{d}(q_2 - q_1) = K(u_2 - u_1),$$

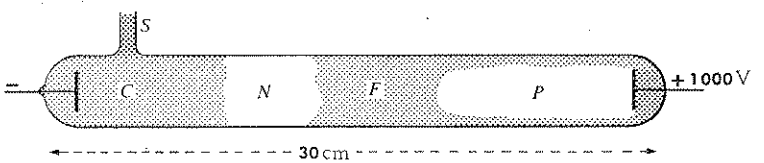
an absolute value can be found for the change in charge and so the electronic charge can be determined.

CONDUCTION THROUGH GASES

In Millikan's experiment, the charge of an electron was deduced from the behaviour of oil drops to which electrons had become attached. A convenient way of studying free electrons, i.e. those not attached to individual atoms, is to study the conduction of electricity through gases at low pressure, because the electricity is then carried mainly by free electrons.

3 Discharge tube

Conduction of electricity through gases at low pressure may be investigated by means of a discharge tube which can be connected to a vacuum pump, as shown in Fig. 3. The tube has two metal electrodes about 30 centimetres apart, between which a potential difference of the order of 1 000 volts is applied. The appearance of the discharge and the processes taking place are closely dependent upon the pressure of the gas:



C, Crookes dark space-fast electrons, i.e. cathode rays; F, Faraday dark space; N, negative glow (blue)-atoms ionised; P, positive column (colour depends upon the gas)-atoms excited; S, to vacuum pump.

Fig. 3 Discharge tube at a pressure of 0·1 millimetre of mercury

a At atmospheric pressure no current will pass for the potential difference which we are considering.

b As the pressure is reduced the whole of the gas suddenly begins to glow with a colour which depends upon the type of gas in the tube. This glow is known as the *positive column* P and is the source of light in sodium or mercury street lamps and in many advertising signs (5 mm Hg).

c As the pressure is further reduced dark spaces develop as shown in Fig. 3, the luminous region moves further from the cathode and there is a dark region behind it which is called the *Faraday dark space* F. On the other side of the dark region, a *negative glow* N is seen, which is always blue irrespective of the type of gas in the tube, and this is separated from the cathode by another dark region known as *Crookes dark space* C. The cathode also sometimes glows blue .

d When the pressure is reduced to about 10^{-3} mm Hg or less, the positive column and negative glow are no longer present and Crookes dark space fills the whole length of the tube. The walls of the tube in front of the cathode fluoresce where Crookes dark space reaches them, and the colour depends upon the type of glass from which the tube is made.

This last state of discharge is of particular interest when studying electrons, because Crookes dark space contains *cathode rays* which, as we shall see on p. 38, consist of fast moving electrons. These electrons originate in the metal forming the cathode and are released by the impact of positive ions as explained below. They are accelerated rapidly after they leave the cathode and soon acquire a high velocity. When they impinge upon the walls of the tube their energy causes the glass to fluoresce.

e When the pressure is reduced still further the discharge ceases because there are not enough positive ions to release the cathode ray electrons.

Positive ions are produced when fast moving electrons collide with the neutral molecules of the gas in the tube; some of the ions will be attracted towards the cathode and will strike it with considerable energy, thereby releasing further electrons from the metal of which the cathode is made. Thus a positive ion formed by a stray electron will release further electrons from the cathode and the process is cumulative, so that when once started the discharge will be maintained so long as the potential difference is applied across the tube.

The conduction of electricity at very low pressures is almost entirely due to free electrons, which are much lighter than positive ions and are therefore much more mobile. For example, a positive ion of neon is 40 000 times heavier than an electron, so that an electron accelerated through the same

potential difference and therefore having the same kinetic energy as a neon ion, will move 200 times as fast ($\sqrt{40\,000} = 200$).

*4 Explanation of the appearance of gas discharge

At low pressures the discharge effects depend mainly upon collisions between electrons and atoms. An incident electron can cause ionisation, or alternatively it can pass on some of its energy to an atom, which is then said to be *excited*, and the atom normally loses this extra energy by radiating light whose *colours are characteristic of the type of atom*: this usually occurs when the incident electrons have less energy than that required for ionisation. When atoms are ionised, however, some of the positive ions recombine with free electrons and energy is released, because potential energy is always lost when two attracting bodies come closer together. The energy can be emitted in the form of light which is usually at the short wave end of the visible spectrum, so the recombination of *ions* is usually accompanied by the emission of *blue light*.

Let us consider again the discharge at a pressure of 0·1 millimetre of mercury as shown in Fig. 3; this includes all the variations observed at other pressures.

a Positive ions are accelerated towards the cathode and when they strike it they release electrons from the cathode. These electrons constitute the cathode rays.

b It is found experimentally that most of the potential drop across the tube occurs within a few centimetres from the cathode so that the field in this region is very strong. Electrons are therefore accelerated rapidly and have a high velocity as they move through Crookes dark space. No glow is observed until they collide with matter, and the average distance through which they travel before a collision depends upon the concentration of the atoms in the tube, and hence upon the pressure. Therefore Crookes dark space becomes longer as the pressure is reduced.

c When these fast electrons collide with atoms they ionise many of them. Some of the positive ions so formed recombine with the free electrons and in this process they emit blue light as described above, which is seen as the negative glow.

d The electrons are slowed down by collisions in the negative glow region so that when they enter the Faraday dark space they have comparatively little energy but are gradually accelerated by the weak field there.

e In the positive column the electrons have regained sufficient energy to excite the atoms (rather than ionise them). When the atoms return to the un-excited state, they emit light of a colour which is characteristic of the

atom, so that the colour of the positive column varies from one gas to another. The positive column is sometimes striated as the electrons alternately lose energy by collisions and regain enough energy for excitation.

To summarise: positive ions striking the cathode release electrons from it which are known as cathode rays. Crookes dark space contains cathode ray electrons which have been rapidly accelerated. The negative glow is due to the recombination of ions produced by impact of fast-moving electrons with neutral atoms. In the Faraday dark space the electrons have been slowed down but are gradually accelerated. In the positive column, light characteristic of the gas is emitted by atoms which have been excited by the impact of electrons of intermediate energy.

5 Cathode rays: their nature and properties

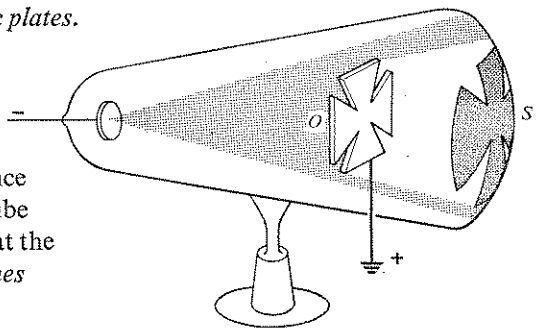
In the preceding explanations we have assumed that cathode rays consist of electrons. Let us now consider the experimental evidence for this assumption.

In order to study the nature and properties of cathode rays a number of specially designed low-pressure discharge tubes have been constructed. In these tubes the anode is usually earthed and a negative potential of about −1 000 volts is applied to the cathode. The pressure is so low that Crookes dark space extends down the whole length of the tube.

a By placing suitable targets opposite to the cathode, it can be shown that the cathode rays cause *fluorescence* when they strike glass, zinc sulphide, and certain other materials.

b They affect *photographic plates.*

c If an obstacle is placed in their path then a clearly defined shadow is formed in the fluorescence at the end of the glass tube (Fig. 4) which shows that the rays travel in *straight lines* from the cathode.



O, obstacle; S, shadow.

Fig. 4. Shadow formed by obstacle in path of cathode rays—showing cathode rays travel in straight lines

d If the cathode is concave and a small piece of platinum is placed at the centre of curvature it soon becomes white hot, showing that the rays *heat* a target on which they fall.

e The above experiment also shows that the rays are emitted at *right-angles* to the cathode surface and that the position of the anode has little effect.

f If the rays strike a target containing heavy atoms then the target is found to emit *X-rays.*

g By using a narrow beam of cathode rays making a small fluorescent spot on the glass walls at the end of the tube, it can be shown that the rays are deflected by a *magnetic field* (Fig. 5).

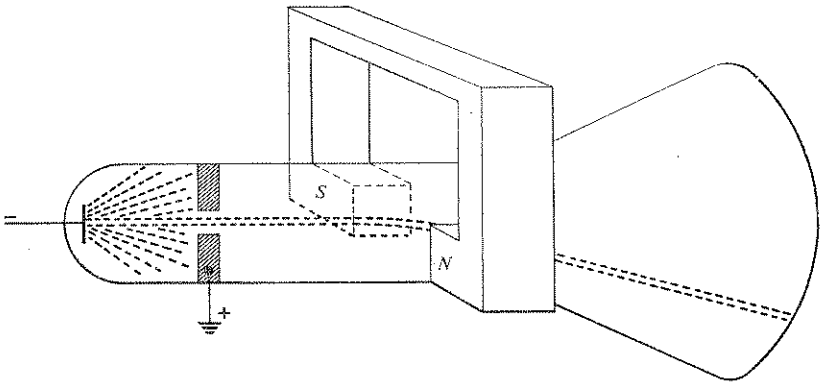


Fig. 5 Cathode rays—deflection in magnetic field

h In a similar way the rays can be shown to be deflected by an *electric field* towards the positively charged plate (Fig. 6).

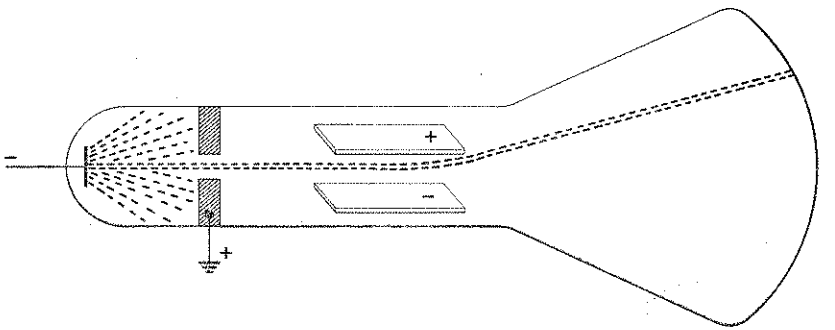
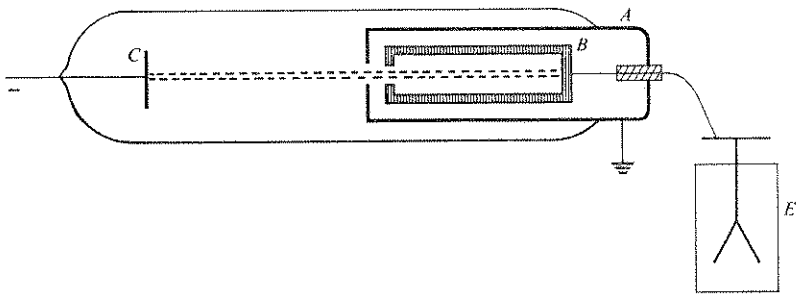


Fig. 6 Cathode rays—deflection in electric field

In the above, properties *a* to *f* give no indication as to the nature of cathode rays except that they convey energy. If they were electromagnetic waves, however, they would not be affected by electric and magnetic fields, so that their deflections in experiments *g* and *h* above show that they must be of some other form. The direction in which they are deflected in an electric field is consistent with their carrying a negative charge, and in a magnetic field the deflection is such as would be experienced by a conventional current (i.e. positive charge) going *against* the direction of the rays, so that this is also consistent with their carrying a negative charge.



A, anode; B, insulated cylinder into which cathode rays enter; C, cathode; E, electroscope.

Fig. 7 Cathode rays carry negative charge

i A direct demonstration of the nature of the charge can be made by means of the tube shown in Fig. 7. An insulated hollow cylinder B connected to a gold-leaf electroscope E is placed opposite the cathode and is surrounded by an anode A with a small hole at the end. When the rays enter the cylinder through the hole in the anode, the leaves of the electroscope diverge and the charge collected is found to be negative, but when the rays are deflected away from the cylinder by means of a magnet no negative charge is collected. The rays must therefore carry a *negative* charge.

j From measurements on the magnitude of the deflections in a magnetic and an electric field a value can be determined for the ratio $\frac{\text{charge}}{\text{mass}}$ of the particles in the beam (see section 6). The ratio is found to have a finite value and this implies that the particles have a measurable *mass*; hence we can assume that cathode rays consist of beams of material particles.

There are two further properties which are, perhaps, surprising for beams of material particles:

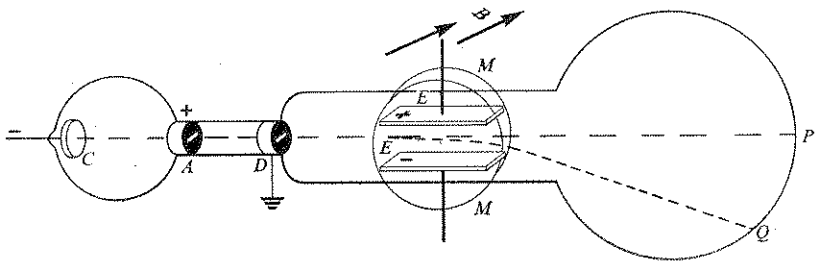
k The particles in the cathode rays can penetrate thin sheets of aluminium and other materials. This can be explained if the dimensions of the particles are small compared with the space inside an atom, for then they can pass through the aluminium atoms.

l Under certain circumstances cathode rays can produce *diffraction* patterns, an example of which is given in Plate 12(b), which shows that these material particles can sometimes exhibit wave-like properties. This can be explained even if we assume that they are material particles (see Chapter 15).

We can conclude, therefore, that cathode rays consist of negatively charged particles having a finite mass. These are the particles to which the name of electrons was first assigned. Their properties, including the value of $\frac{\text{charge}}{\text{mass}}$, do not depend upon the metal used for the cathode nor upon the type of gas originally in the discharge tube, so that electrons can be released from many types of atoms, and this suggests that they are a common constituent of all atoms. The velocity of these electrons can be extremely high, approaching the velocity of light.

The term 'ray' was applied to cathode rays before their true nature was known, and care must be taken to avoid identifying them with electromagnetic radiations such as X-rays and light.

6 Measurement of specific charge $\frac{e}{m}$ of an electron: Thomson's method



A, anode; B, magnetic field (into plane of paper); C, cathode; D, earthed plate; E, electrostatic deflecting plates; M, magnetic field coils (field into plane of paper); P, undeflected position of fluorescent line; Q, position of line with magnetic field.

Fig. 8 Measurement of $\frac{e}{m}$ of electron. (Thomson's method)

The specific charge of an electron, which is defined as the ratio of $\frac{\text{charge}}{\text{mass}}$ was measured by J. J. Thomson in 1897. The apparatus is shown in Fig. 8.

Cathode rays are generated in the section of the tube shown on the left of the diagram, the whole apparatus being evacuated. The electrons entering the rest of the tube are confined to a flat beam by means of a narrow slit about 1 millimetre wide in the anode A and a similar slit in an earthed plate D, so that they make a sharp horizontal line on a fluorescent screen at P.

A magnetic field B is applied perpendicular to the plane of the paper by means of two circular coils M situated outside the tube which are separated by a distance equal to their radius. Such coils are known as *Helmholtz coils* and when a current is sent through them a magnetic field is produced in the central region which is almost uniform and whose magnitude can be estimated from the radius and number of turns in the coils and the size of the current flowing in them.

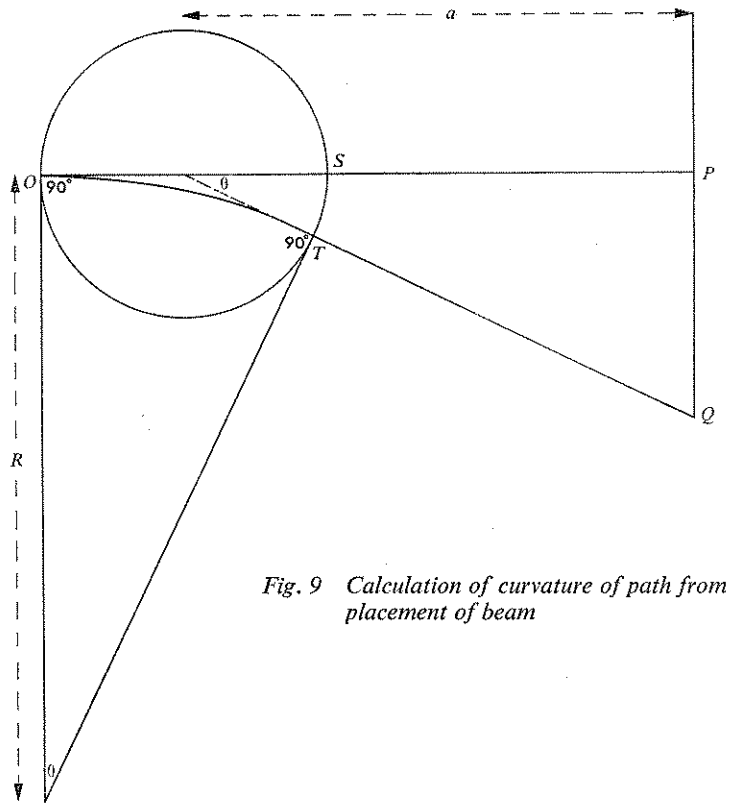


Fig. 9 Calculation of curvature of path from displacement of beam

Referring to Fig. 9, the magnetic field is applied over the length OS of the electron beam. The electrons moving to the right with a velocity u are equivalent to a current i to the left, since the charge of an electron is negative. The magnitude of the current is the charge passing a given point in one second, so that it is equal to the total charge in a length u of the beam;

hence, the current $i = n.e.u.$

where n is the number of electrons per centimetre and $-e$ e.m.u. is the charge of a single electron. Consider a short length s of the beam. The magnetic field B exerts a force on the electrons in this length of beam equal to $B.i.s$ dynes* which is equal to

$$B\,.\,n.e.u\,.\,s \text{ dynes} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

This force acts at right-angles to both the beam and the magnetic field and causes the electrons to move in a circle of radius R. But the force required for circular motion is $\frac{Mu^2}{R}$ dynes,† where M is the total mass of the electrons in this length of beam, i.e. $M = m.n.s.$, where m is the mass of an electron.

Hence force $= \frac{m.n.s\,.\,u^2}{R} = B\,.\,n.e.u\,.\,s$ from equation (1)

$$\therefore \frac{e}{m} = \frac{u}{BR} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The radius of curvature R, can be evaluated by measuring the displacement PQ of the line on the screen if the dimensions of the tube are known, as shown below:

Referring to Fig. 9: θ is small, therefore using radian measure‡

$$\theta = \frac{OT}{R} = \frac{OS}{R}$$

And $\theta = \frac{PQ}{a}$ where a may be taken as the distance between the centre of OS and the end of the tube.

Hence $\frac{OS}{R} = \frac{PQ}{a}$ and therefore $R = \frac{a.OS}{PQ}$

In order to eliminate u from equation (2) above, the beam is restored to its original position P by applying a vertical electrostatic field between the deflecting plates E shown in Fig. 8;

* Force acting perpendicular to a conductor is $B.i.s$ dynes, where s is the length of the conductor carrying a current of i e.m.u. at right-angles to a magnetic field of strength B gauss.

† Force required to maintain motion in a circle equals $\frac{Mu^2}{R}$ dynes towards the centre.

‡ In radian measure $\theta = \frac{\text{arc}}{R}$ and, if small, $\theta = \tan\theta$.

the magnitude of the field X = potential gradient = $\frac{V}{d}$ e.m.u.

where V e.m.u. is the potential difference applied between the plates and d is their separation. The electrostatic force acting on the length s of beam must then exactly balance the magnetic force:

but force = charge × electric field = *n.e.s.* X dynes

Hence *n.e.s.* $X = B$. *n.e.u.* s from equation (1)

$$\therefore u = \frac{X}{B} \text{ where } X = \frac{V}{d}$$

and from equation (2) $\frac{e}{m} = \frac{X}{B^2R}$. The value of this ratio for an electron is found to be 1.759×10^7 e.m.u. g^{-1}.

Since different sets of absolute c.g.s. units have been developed from electromagnetic and electrostatic measurements and in this experiment forces due to both types of fields are employed, great care must be taken to use the same set of units throughout. In the calculations above, electromagnetic units were used for the electrostatic field.†

Historically, this experiment was carried out about twelve years before Millikan had made a reliable measurement of the electronic charge, so that although the specific charge $\frac{e}{m}$ can now be used to evaluate the electronic mass, this information could not be deduced when the experiment was first performed. Since, however, the specific charge of an electron is unique among negative particles, its value was used to identify electrons, for example the particles produced by photo-electric emission (p. 192) were identified as electrons in this way.

***7 Measurement of specific charge e/m of an electron: magnetron method**

The magnetron provides another means of measuring approximately the value of the specific charge of an electron. It consists of a cylindrical anode about 5 centimetres long, and a straight wire lying along its axis to serve as a cathode, the whole being in an evacuated tube. The cathode is heated and this makes it emit electrons (see Chapter 3). The electrons are attracted outwards to the cylindrical anode to which a positive potential is applied, as shown in Fig. 10*a*, and the number which reach the anode can be measured

† 1 e.s.u. of charge = c e.m.u. of charge, where c is the velocity of light (see p. 29).
Field = $\frac{\text{force}}{\text{charge}}$ and hence X_s e.s.u. of field = $\frac{X_m}{c}$ e.m.u. of field.

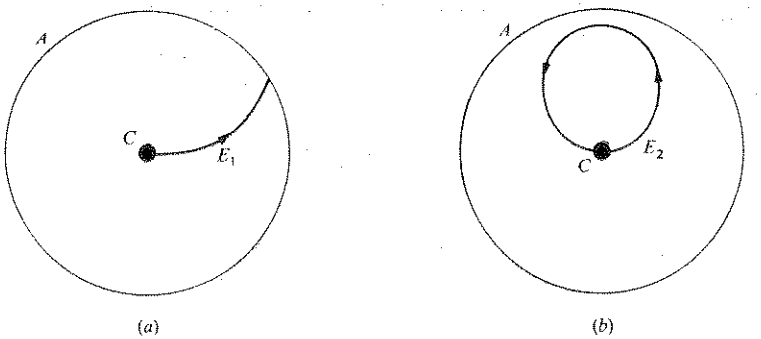


Fig. 10 Measurement of $\frac{e}{m}$ *of electron. (Magnetron method.)*

A, anode; C, cathode; E_1, electron path in weak field—electrons reach anode; E_2, electron path in strong field—anode current is cut off.

by the current in an external circuit. A magnetic field is applied along the axis of the tube by surrounding the tube with a solenoid carrying a current. The magnetic flux is therefore at right-angles to the paths of the electrons which consequently become curved with a radius of curvature given by $\frac{e}{m} = \frac{u}{Br}$ as deduced on p. 43. This will have very little effect on the anode current if the field is small, but when the field reaches a certain value, the anode current is cut off as shown in Fig. 10*b*. It is possible to calculate $\frac{e}{m}$ from the dimensions of the tube, the potential difference between anode and cathode, and the magnetic field when the current is just cut off.

In practice the current does not become cut off very sharply when the field increases, because electrons are emitted from the cathode with a range of velocities and this results in the faster ones reaching the anode when the slower ones are just prevented by the field from getting there.

***8 Simplified theory of magnetron**

Since the electric field inside the magnetron is radial, it is very strong near the central cathode (see Fig. 56, page 118). The electrons therefore experience a very strong force in this region and acquire almost their maximum velocity within a very short distance of the centre. If we assume that their velocity on emission from the cathode is zero, then the maximum velocity is given by $\frac{1}{2}mu^2 = eV$ (see section **9** below).

$$\text{hence } u = \sqrt{\frac{2eV}{m}}$$

We shall assume that they move with this velocity throughout their path.

The electrons describe a circular path in the magnetic field of radius given by $\frac{e}{m} = \frac{u}{Br}$ (p. 43). As will be seen from Fig. 10*b*, cut off will occur when the radius of curvature of the path is half that of the anode, i.e. $\frac{R}{2}$,

$$\text{and hence } \frac{e}{m} = \frac{2u}{BR} = \frac{2}{BR}\sqrt{\frac{2eV}{m}}$$

and since all factors except the ratio e/m in this expression are known, the specific charge can be evaluated. (In practice the paths will be slightly heart-shaped because the electron velocity will be somewhat greater near the anode and this will make the curvature slightly less.)

9 Velocity of an accelerated electron

The velocity of an electron in a low pressure tube such as that used by Thomson can be calculated from the potential difference applied across the tube. If an electron is accelerated from rest through a potential difference of V volts, then the energy it acquires is equal to charge × potential difference. Using absolute electromagnetic units, the charge is e e.m.u. and the potential difference is $V \times 10^8$ e.m.u.

Hence the energy acquired, $\frac{1}{2}mu^2 = e \times V \times 10^8$ ergs.

$$\therefore \quad \frac{e}{m} = \frac{u^2}{2 \times V \times 10^8} \text{ e.m.u. g}^{-1}.$$

Care must be taken to use absolute units (either e.m.u. or e.s.u.) since kinetic energy is normally measured in absolute units.

10 Electrons—summary and conclusion

We have seen that an electron is a negatively charged particle which is a constituent of all neutral atoms and is the basic unit of electricity. An electron has a charge, usually designated by $e = -1{\cdot}602 \times 10^{-19}$ coulomb, and a very small mass of 0·000 55 a.m.u. which equals $9{\cdot}1 \times 10^{-28}$g, or about $\frac{1}{1840}$ times that of a proton; (e is sometimes used to denote the numerical value of the charge).

Free electrons can pass right through atoms because their dimensions are small compared with those of an atom as a whole, and therefore electrons can penetrate through small thicknesses of solid material. As they pass through matter, electrons can repel orbital electrons to such an extent that the latter are removed from their atoms. Electrons, therefore, cause ionisation, but in so doing they lose energy so that they slow down and finally stop; thus their powers of penetration are limited. The positions of

the ions produced by the passage of electrons through a gas are shown by the thin lines in Plate 3.

If an electron spins on its own axis (like the *daily* rotation of the earth) it is found to have a magnetic moment associated with it, but the details of this are outside the scope of this book. However, the effect is of great importance in a more advanced study of atomic structure, and the spin can also account for the magnetic properties of materials (see p. 189).

Beams of moving electrons constitute cathode rays. As we shall see in the next chapter, electron beams are used in X-ray tubes, electron microscopes, thermionic valves, and cathode ray tubes.

As we shall also see subsequently, electrons constituting part of an atom are responsible for magnetism, for the spectra emitted by atoms, and for chemical combinations of elements. When forming part of a metal crystal, some electrons are responsible for the conduction of electricity; they can be released from the metal during the processes of low pressure discharge, and during thermionic and photo-electric emission.

Problems on Chapter Two

Electrolysis

1. State Faraday's laws of electrolysis.

Evaluate the electronic charge using the following data: mass of silver deposited by 1 coulomb of electricity is 0·001 118 g; valency of silver is 1; atomic weight of silver is 107·9 a.m.u.; Avogadro's number = $6{\cdot}023 \times 10^{23}$ atoms per gram-atom.

2. Explain how the value of the electronic charge can be estimated from a knowledge of the electro-chemical equivalent of silver and of the Avogadro number N. What assumptions are involved in your argument? O 64 I–7.

3. Give an account of an experiment for the determination of the electronic charge.

If the specific charge of the electron is $1{\cdot}76 \times 10^{-8}$ coulomb/gramme and the electro-chemical equivalent of hydrogen is $1{\cdot}045 \times 10^{-5}$ gramme/coulomb, calculate the ratio of the masses of the hydrogen atom and the electron. L 63 A II–11

Electronic charge, e

4. Describe an experiment which has been carried out to determine the value of the electronic charge.

If this charge is $1{\cdot}60 \times 10^{-19}$ coulomb, calculate the number of atoms in a gram-atom given that a steady current of 1·00 amp. releases 3·76 g of hydrogen per 100 hours in electrolysis. L W65 II–11

5. Outline briefly the evidence for the view that electricity is discontinuous in nature.

Explain the principles of a method by which the fundamental unit of electric charge (i.e. the charge on an electron) has been accurately measured, and show how the result is calculated from the observations made.

S 64 II–11

6. Give an account of a method by which the charge associated with an electron has been measured.

Taking the electronic charge to be $-1{\cdot}60\times10^{-20}$ e.m.u. calculate the potential difference in volts necessary to be maintained between two horizontal conducting plates, one 0·50 cm above the other, so that a small oil drop of mass $1{\cdot}31\times10^{-11}$ gramme with two electrons attached to it, remains in equilibrium between them. Which plate would be at the positive potential? ($g = 980$ cm sec^{-2}) L 63 II–11

7. Describe a method of determining the charge on an electron. Two horizontal metal plates are arranged one above the other. The vertical height of the space between them is 2·04 cm and the upper plate is maintained at a positive potential of 1 200 volts, while the lower plate is earthed. Calculate the number of electrons that must be attached to a small oil drop of mass $1{\cdot}92\times10^{-11}$ gramme in order that it shall remain stationary between the plates. (Take the electronic charge as $-1{\cdot}60\times10^{-20}$ e.m.u.; $g=980$ cm sec^{-2}). L specimen II–11

8. Give an account of the structure of atoms including the significance of the terms *atomic mass* and *atomic number*. State how the fundamental particles of which atoms are composed differ from each other as regards mass and electric charge. (See Chapters 4 and 11.)

A p.d. of 2·0 e.s.u. is maintained between two identical horizontal metal plates placed 4·0 cm apart, one above the other, in an evacuated vessel. Particles each with mass $9{\cdot}1\times10^{-28}$ gramme and electric charge $-4{\cdot}8\times10^{-10}$ e.s.u. are emitted with negligible velocity from the plate at the lower potential. For one of the particles calculate (*a*) the ratio of electrical force to gravitational force upon it, (*b*) its acceleration, and (*c*) the kinetic energy it acquires on reaching the other plate. ($g=981$ cm sec^{-2}.) N 64 II–7

9. A cloud of very small negatively charged water drops was produced in air in a closed vessel containing a pair of horizontal uncharged metal plates 5·0 mm apart, and the top of the cloud fell from the upper to the lower plate in 50 seconds. The top of a similar cloud fell over this distance in 28 seconds when the plates differed in potential by 1 200 volts. Obtain a value for the charge on a single drop, assuming the drops to be of equal size and to have similar charges.

Criticise this experiment as a method for determining electronic charge.

Describe *briefly* how Millikan modified and improved it. (Take the viscosity of air as $1{\cdot}8\times10^{-4}$ poise, $300V=1$ e.s.u., $g=980$ cm sec^{-2}.)

L Sp. 61–12

Specific charge

10. Distinguish between the mechanisms of current conduction in (*a*) metals, (*b*) electrolytes, and (*c*) gases at low pressures.

From the following information find the charge and mass of the electron. (i) A current of 2·00 amps flowing for 30 minutes through a copper voltameter deposits 1·19 g of copper on the cathode. Copper is divalent and its atomic mass is 63·5. The number of atoms per gram-atom is $6{\cdot}02\times10^{23}$; (ii) an electron moves with constant speed of $2{\cdot}00\times10^{9}$ cm sec^{-1} and describes a circular arc of radius 9·10 cm in a plane normal to which there exists a uniform magnetic field of 12·5 oersted. N 61 II–12

11. Describe a method by which the charge per unit mass of an electron has been determined.

An electron is accelerated from rest through a potential difference of 200 volts. Find the velocity that it acquires. (Take the value of $\frac{e}{m}$ as $1{\cdot}76\times10^{7}$ e.m.u. gramme^{-1}; 1 volt $=10^{8}$ e.m.u.) L W63 II–10

12. Describe and give the theory of an experiment to determine the value of $\frac{e}{m}$ for an electron.

If this value is actually $1{\cdot}76\times10^{7}$ e.m.u. gramme^{-1} ($1{\cdot}76\times10^{11}$ amp. sec kg^{-1}) calculate the velocity of an electron of energy 10 000 electronvolts moving in a region of zero potential. (1 volt $=10^{8}$ e.m.u.) L W64 II–10

13. Describe a method for measuring the charge per unit mass for the electron, showing how the value is calculated from the observations.

An ion for which the charge per unit mass is $4{\cdot}4\times10^{3}$ e.m.u. gramme^{-1} has a velocity of $3{\cdot}52\times10^{7}$ cm. sec^{-1} and moves in a circular orbit in a magnetic field of induction 4×10^{3} gauss. What will be the radius of the orbit? L 61 II–11

14. Show that an electron travelling at constant speed in a direction at right-angles to a uniform magnetic field, describes a circular path, and find an expression for the radius. Show also that, in general, an electron travelling at constant speed in a uniform magnetic field describes a helical path.

Describe as fully as you can one method by which the ratio e/m for the electron has been determined. O Sp. 63–1

15. Describe and give the essential theory of an experiment for the accurate determination of the specific charge (e/m) of an electron.

Calculate the radius of curvature of the path of an electron which has

been accelerated from rest through a potential difference of 60 volts, when it passes across a uniform magnetic field of strength 0·80 oersted applied at right-angles to the trajectory of the electron. (Assume $e/m = -1{\cdot}8 \times 10^8$ coulomb. g^{-1} and that relativistic effects may be neglected.)

L Sp. specimen 12

16. State Faraday's laws of electrolysis.

(*a*) The electro-chemical equivalent of silver is $1{\cdot}118 \times 10^{-3}$ g coulomb^{-1} and the atomic weight of silver is 108. Calculate the ratio of charge to mass of a hydrogen ion.

(*b*) An electron moving with a speed of 5×10^5 metre sec^{-1} at right-angles to a magnetic field of 10 oersteds (magnetic flux of 10^{-3} volt sec metre^{-2}) describes a circle of radius 2·83 mm. Calculate the ratio of charge to mass of an electron.

(*c*) Deduce the ratio of the masses of the electron and the hydrogen ion.

S 63 II–9

(*The following question illustrates an alternative method for evaluating specific charge: particles having the same specific charge lie on a parabola.*)

17. Describe and account for the form of the path of a charged particle which enters (*a*) a uniform magnetic field, (*b*) a uniform electric field, travelling initially with constant velocity perpendicular to the lines of force.

A fine collimated beam of positive ions from a discharge tube passes through a short region where exist a uniform magnetic and a uniform electric field superimposed and acting in the same direction perpendicular to the axis of the beam. After leaving the field the beam traverses a field-free evacuated space and impinges upon a photographic plate whose plane is perpendicular to the undisplaced beam. Deduce expressions for the deflection of the beam produced by either field alone, assuming the deflection to be small and the length of the path in the field to be much less than the distance of the field region to the plate. Hence show that the action of the combined fields is to cause all ions having the same value of mass per unit charge m/e, but different velocities, to strike the plate along a parabola whose position depends upon the value of m/e.

In certain experiments of this nature using oxygen, parabolas were observed corresponding to values of m/e both eight and sixteen times the value for the proton; while using neon, parabolas were observed corresponding to values 20 and 22. Comment briefly on these two sets of results.

L Sp. 64–12

Chapter Three

Applications of Electron Beams

In an X-ray tube (see p. 205) a beam of fast electrons strikes a heavy material which absorbs the energy and converts some of it into X-rays.

Another use of such beams is in an electron microscope in which an electron beam is used to 'illuminate' an object (see p. 240). Electron microscopes have made possible the observation of viruses and other very small objects which are 1 000 times smaller than those that can be seen using an optical microscope.

Two further applications which we shall consider in some detail are thermionic valves and cathode ray tubes.

THERMIONIC VALVES

1 Thermionic emission

Some of the electrons in a metal are so loosely bound to individual atoms that they may be considered as moving freely inside the crystal structure of the metal as a whole (see p. 187). These electrons can escape from the surface if they have enough energy to overcome the attraction of the positive ions which form the metal crystals. One method of supplying the requisite amount of energy is to heat the metal as a whole, since some of the heat energy takes the form of kinetic energy of these free electrons.

At ordinary temperatures the number of electrons escaping is negligible, but if a metal is very hot a copious supply can be released; this process is known as *thermionic emission* and is the source of electrons forming the beams in thermionic valves (e.g. diode and triode), cathode ray tubes, and most types of X-ray tubes. The process can be studied by means of a diode.

2 Diode (two-electrode valve)

A diode is a two electrode valve similar to that illustrated in Fig. 18. page 57, except that it has no spiral 'grid' wire G. The cathode K is a metal wire which can be 'directly heated' by passing a current through it or 'indirectly heated' as will be described on page 65. It is surrounded by a cylindrical anode A and the two electrodes are in an evacuated envelope to allow the electrons to move freely. The cathode can be of tungsten; it is often coated with barium oxide or strontium oxide so that electrons are emitted at a temperature of about 800°C–1 000° C whereas pure tungsten

needs to be at 2 500°C before emission is significant. The symbol for a diode is used in Fig. 11.

By applying a positive potential of about 100 volts to the anode, the electrons can be drawn across the tube as fast as they are emitted by the cathode. Their rate of emission can then be measured by means of a milliammeter connected to the anode, as shown in Fig. 11. Using such a circuit, Richardson carried out some experiments on thermionic emission in which he controlled the temperature of the cathode by adjusting the heating current, and estimated the temperature from its electrical resistance. He showed empirically that the rate of emission of electrons depends upon the absolute temperature T and is negligibly small at low temperatures (Richardson's empirical formula for emission rate is: emission $= Ae^{-B/T}$, where A and B are constants for a particular metal).†

3 Variation of current with anode potential

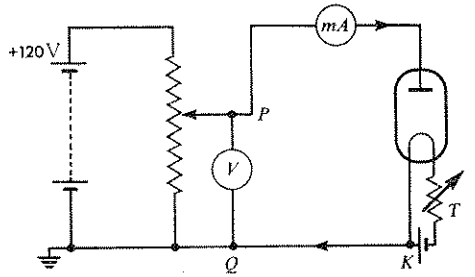
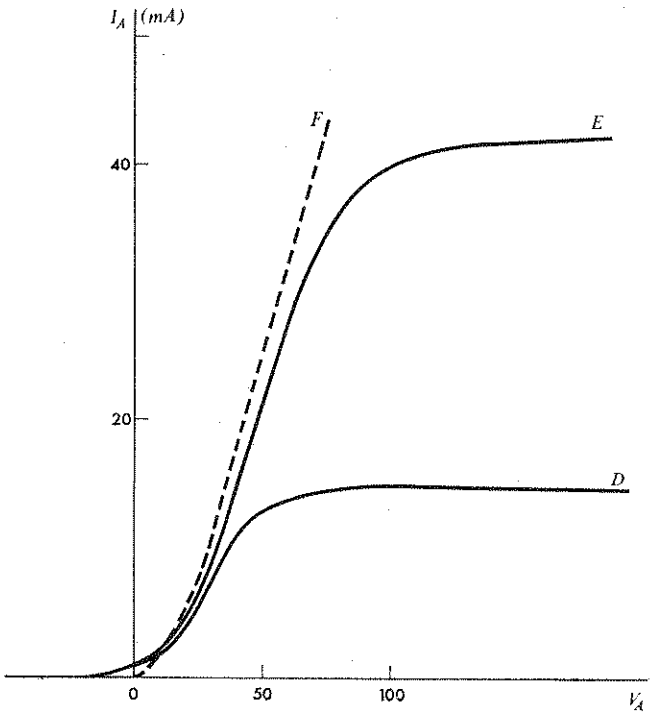


Fig. 11 Circuit for diode characteristic (I_A : V_A). *Cathode temperature adjusted by T*

The circuit shown in Fig. 11 can also be used to investigate how the current passing through the diode depends upon the potential of the anode. The heating current is kept constant, the potential difference between cathode and anode is adjusted by means of the potential divider circuit as shown in the diagram, and the current is measured using a milliammeter connected to the anode (the arrows indicate the direction of positive current). Negative voltages can also be supplied to the anode by reversing the connections to the supply. The results can be plotted on a graph of current : voltage which is known as a *characteristic curve*; it takes the form shown in Fig. 12,

† Theoretical considerations give the formula: emission $= AT^2e^{-B/T}$, but since the factor T^2 changes very much less rapidly than $e^{-B/T}$, the empirical and theoretical formulae are not very different.



D characteristic for temperature of 2 200°C; E, characteristic for temperature of 2 300°C; F, theoretical curve $I \propto V^{3/2}$; I_A, anode current in milliamps; V_A, anode voltage.
Fig. 12 Diode characteristics

where the lower line represents the characteristic for a small heating current and the upper line is the corresponding curve when the heating current is increased, thereby raising the temperature of the cathode.

It is seen that the anode current does not reach its maximum, or 'saturation' value, until the potential difference between the anode and cathode is fairly large. This is because the electrons emitted by the hot cathode tend to float near it, thereby producing a negative *space charge*, as shown in Fig. 13.

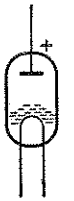


Fig. 13 Negative space charge, formed by electrons near cathode

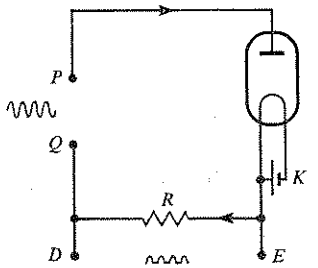
The effect of the field due to this charge is to repel electrons emitted by the cathode, with the result that when the anode potential is small only a few electrons are removed from the vicinity of the cathode so that the number reaching the anode is small. The very small current crossing the tube when the anode is negative is accounted for by the finite velocity with which the electrons are emitted from the cathode, and this enables a few of them to reach the anode in spite of electrical repulsion.

As the anode potential increases, the electrons forming the space charge are more readily attracted to the anode, so allowing an easier flow of electrons from cathode to anode, and thus the anode current is increased. This is represented by the first parts of the curves of Fig. 12, where it is found that the current $I_A \propto V_A^{3/2}$ approximately (F). When the anode potential increases beyond a certain value then the electrons are removed as fast as they are emitted and a saturation effect is observed. The saturation current depends upon the temperature of the cathode, being larger when the heating current is increased, and the corresponding anode potential when saturation is observed also increases a little with cathode temperature.

The graphs described above using the circuit of Fig. 11 are known as *static characteristics*. If there is a high resistance in the anode-cathode circuit, as for example in the circuit shown in Fig. 14, then the results are modified and the graphs are then called *dynamic* characteristics.

4 Diode as a rectifier

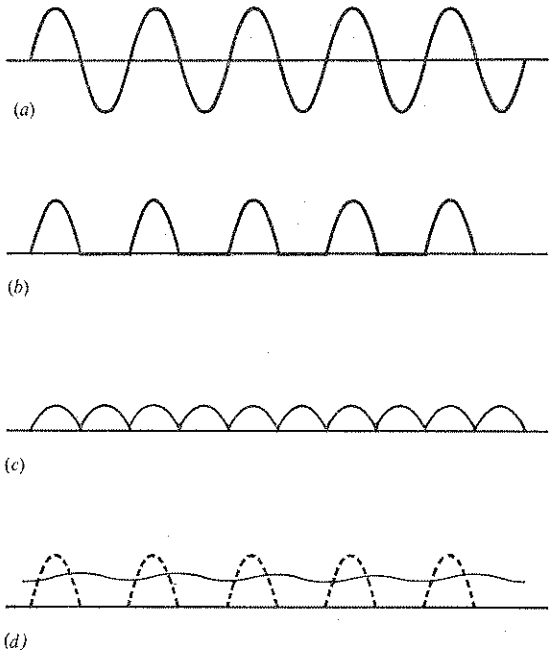
Referring to Fig. 12 it is seen that a negative potential applied to the anode produces a negligibly small current through the tube, whereas a positive potential allows a current to pass. The diode, therefore, only passes a current when the potential difference between cathode and anode is in one direction and hence the name of *valve*. A diode can therefore *rectify* an alternating voltage.



Alternating input applied between P and Q. Uni-directional output taken between D and E.

Fig. 14 Circuit for rectifying alternating voltage

The circuit used for rectification is shown in Fig. 14, and it is seen that this is essentially similar to Fig. 11. The alternating input is applied between P and Q and the appliance through which the rectified current is to be passed is usually placed in the cathode side of the circuit, between D and E: if a rectified *voltage* is required, then a high resistance R is connected between D and E, and the output, equal to RI volts, is taken from between its ends. Thus an input voltage of the form shown in Fig. 15*a* gives the output shown in Fig. 15*b* which varies in magnitude but always flows in the same direction, and such a circuit is known as a *half-wave rectifier*.

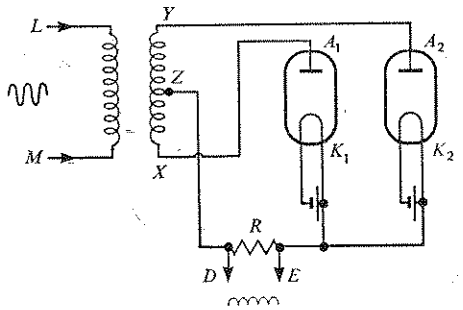


(*a*) alternating voltage; (*b*) half-wave rectification (unsmoothed); (*c*) full-wave rectification; (*d*) smoothed direct voltage.

Fig. 15 Rectification of alternating voltage

5 Full-wave rectifier

In order to obtain a more even output a *full-wave rectifier* circuit may be used as shown in Fig. 16. It incorporates two diodes, both of which have their cathodes connected to the centre tap of the secondary of a transformer.



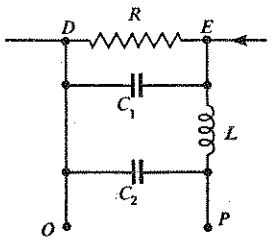
Alternating input applied between L and M. Output, between E and D, is rectified but unsmoothed (see Fig. 15*c*).

Fig. 16 Full-wave rectifier circuit

The anodes are connected to the opposite ends of this secondary coil and the alternating input voltage is applied across the primary coil. When X is positive, relative to Z (Fig. 16) then the diode A_1K_1 passes current, and when Y is positive then the diode A_2K_2 passes current. Hence the output voltage developed across the resistance between D and E is of the form shown in Fig. 15*c*. The diodes are sometimes contained in a single envelope having a common cathode and two separate anodes.

6 Smoothing unit

The rectified output developed between D and E of Fig. 16 can be further *smoothed* as shown in Fig. 17, by connecting a fairly large condenser C_1 of, say, 30 μ F in parallel with the output resistance R, i.e. between D and E of Fig. 16. When the current from the diode is a maximum then the condenser is charged up, and when the current from the diode falls then the condenser begins to discharge through R; hence the current through R becomes much steadier, developing a voltage across it of the form shown in Fig. 15*d*.



Unsmoothed, rectified input developed between E and D (see Fig. 15*c*). Output, between O and P is rectified and smooth (see Fig. 15*d*).

Fig. 17 Smoothing unit

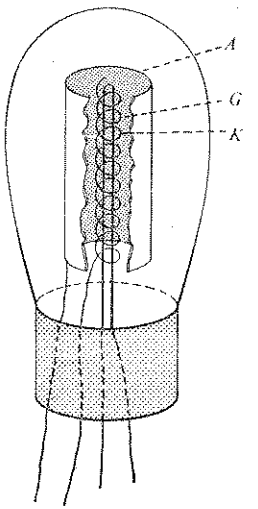
The slight ripple can almost entirely be removed by means of the circuit given in Fig. 17 which is known as a *smoothing unit*. The inductance, L, which may be a few turns of thick copper wire on an iron core, offers very little resistance to direct current but has a high 'impedance' for changing current, and any fluctuations which reach the other side are further smoothed by the second large condenser C_2.†

A complete unit, called a *power pack*, incorporating a full wave rectifier and a smoothing unit, often replaces a high tension battery and it can be operated from alternating mains to supply a steady direct voltage.

7 Triode (three electrode valve)

It is seen that the action of a diode is strongly influenced by the field due to the space charge near the cathode. This field can be modified considerably by surrounding the cathode with a coil of wire which is maintained at a known potential (G in Fig. 18). The wire forms a third electrode, known as a grid, and is sufficiently open for electrons to pass through it freely from cathode to anode.

The relation between grid potential, anode potential, and anode current



A, anode; G, grid; K, cathode.

Fig. 18 Triode

† The 'impedance' of a component to alternating current corresponds to a 'resistance' to direct current. For an inductance L having a negligible resistance to direct current, the impedance is $L\omega$ and for a capacitance C it is $1/C\omega$, where ω is $2\pi \times$ frequency of the alternating current through the component; (for direct current $\omega = 0$, making $L\omega = 0$ and $1/C\omega = \infty$).

for a given heating current can be investigated using the circuit shown in Fig. 19. The grid potential is first kept constant and graphs known as anode characteristics may be drawn giving the relation between anode current and anode potential; these take the form shown in Fig. 20.

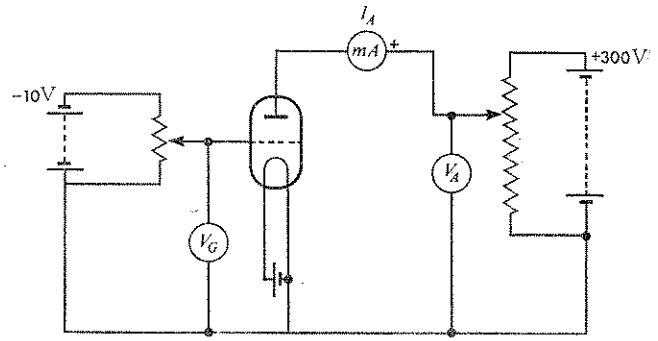
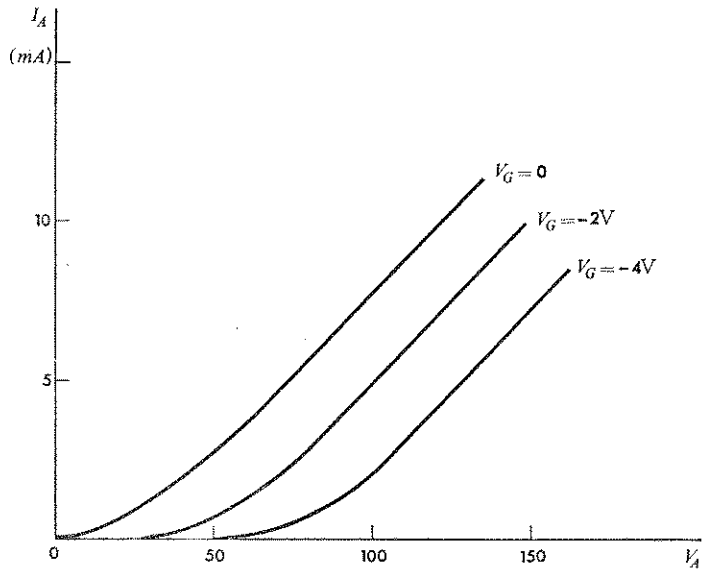


Fig. 19 Circuit for triode characteristics



I_A, anode current in milliamps; V_A, anode potential; V_G, grid potential.

Fig. 20 Anode characteristic of triode $I_A : V_A$ *for different values of grid potential* V_G

The family of graphs of anode current I_A plotted against grid potential, V_G, called the mutual characteristics, is shown in Fig. 21; for larger values of the anode potential, V_A, the currents will be larger, so that the graphs lie one above another. The first part of the characteristic is similar to those already considered while the part of the curve to the right of the current axis is of little practical interest as the valve is normally operated with the grid at a negative potential relative to the cathode. This latter is because, if the grid potential became positive, some of the electrons would be collected by it instead of them going to the anode, and this is usually undesirable because it destroys the linearity of this part of the characteristic.

8 Valve parameters

Since the grid is much closer to the cathode than is the anode, it has a greater influence on the space charge and thus on the flow of electrons through the valve. It will be seen from the graphs of Fig. 21 that a change of

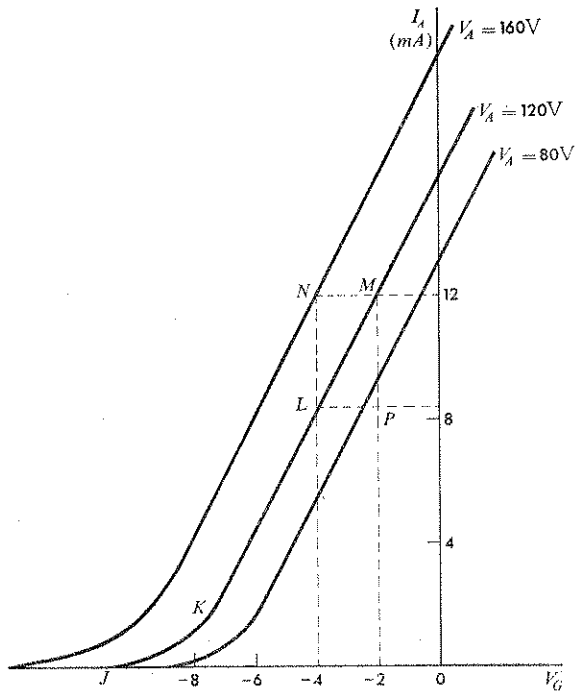


Fig. 21 Mutual characteristics of triode I_A: V_G *for different values of anode potential* V_A

only about 2 volts in grid potential (LM) has the same effect on the anode current as a change of 40 volts in the anode potential (LN).

The *amplification factor*, μ, of the triode is defined as the ratio of the increase in anode voltage to the increase in grid voltage, which produces the same change in anode current,

$$\text{i.e. } \mu = \frac{\delta V_A}{\delta V_G}$$

It is a constant for a particular triode so long as the straight parts of the characteristics are considered. Thus for the triode of Fig. 21.

$$\mu = \frac{160-120}{2} = 20$$

The ratio of change in anode current to change in grid potential, $\frac{\delta I_A}{\delta V_G}$, is called the *mutual conductance* of the triode, and the ratio of change in anode potential to change in anode current, $\frac{\delta V_A}{\delta I_A}$ is known as the *anode impedance*. These quantities are sometimes referred to as the *valve parameters*.

Thus:

amplification factor $\mu = \frac{\delta V_A}{\delta V_G}$ for a given δI_A,

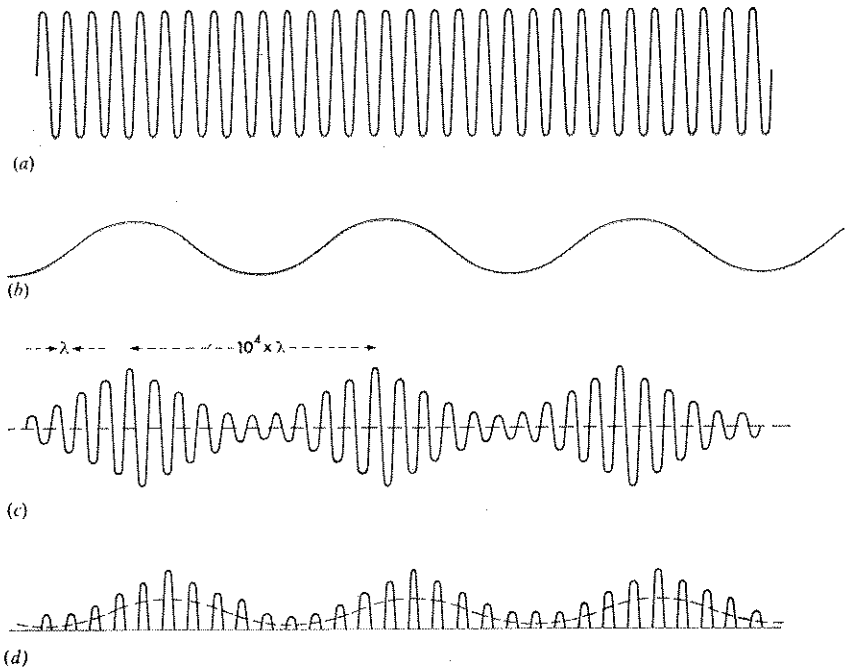
mutual conductance $= \frac{\delta I_A}{\delta V_G}$,

anode impedance $= \frac{\delta V_A}{\delta I_A}$,

where all these expressions refer to the straight parts of the characteristics.

9 Uses of a triode

The output from a radio transmitter consists of a *carrier wave* (Fig. 22*a*) whose frequency is constant and characteristic of the transmitting station, lying between about 100 kc/s for long waves and 300 Mc/s for V.H.F. (very high frequency). One method of transmitting messages is to 'modulate' the amplitude of the carrier wave with the audio frequency to be sent out (Fig. 22*b*) so that the resultant waveform is as shown in Fig. 22*c*. At the receiver, a loudspeaker will not respond to high frequency variations and it will therefore follow the mean value of the wave, which is zero. If, however, all the negative part of the wave is destroyed, then the effect on the loudspeaker will be a positive current varying in magnitude with the amplitude of the transmitted wave, as shown by the broken line in Fig. 22*d*, and so the effective current through the speaker will correspond exactly to the audio frequency message which modulated the wave at the transmitter;



(a) *Radio frequency 'carrier' wave.*
(b) *Audio frequency variations corresponding to sound wave to be transmitted.*
(c) *Amplitude modulated wave sent to receiver (mean value is zero).*
(d) *Rectified wave has mean value similar to* (b).
(*In practice, wave length of modulating voltage* ~ 10^4 × *wavelength of radio frequency wave.*)

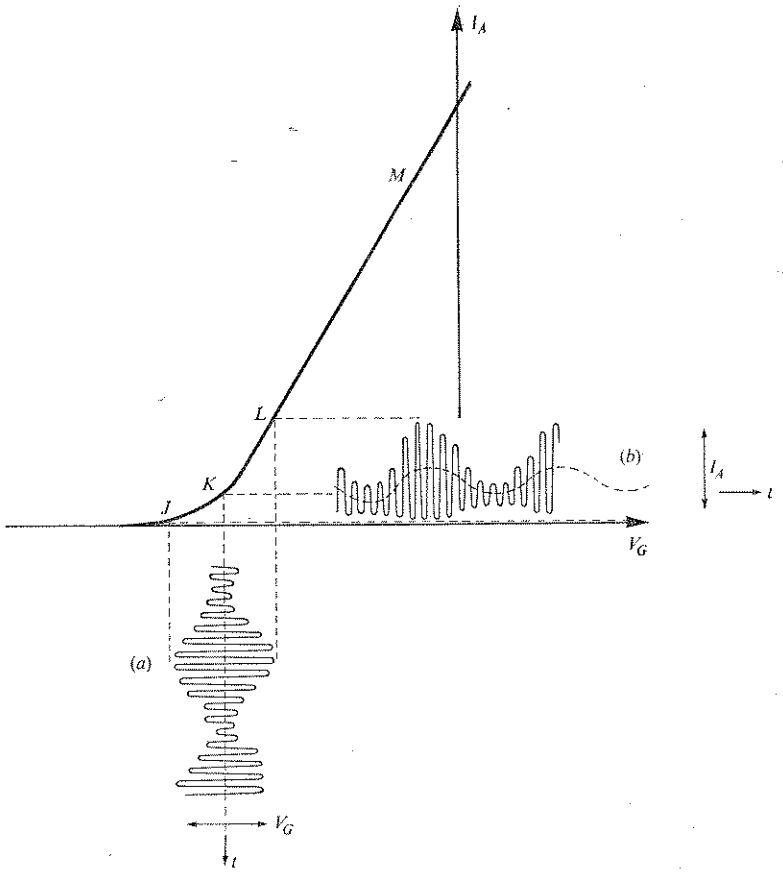
Fig. 22 De-modulation of radio waves

these variations are slow enough for the speaker to respond to them. This process of de-modulation is often referred to as *detection*.

Thus at the receiver the radio signal requires *detection*, which can be accomplished by rectification. The waves at the receiving aerial are very weak and they therefore require *amplification*. At the transmitter, the a.c. carrier wave needs to be generated, and this process is called *oscillation*. A triode can be used for each of these three purposes.

10 Triode as a detector

In order to detect, or de-modulate, the signal, the amplitude modulated wave is rectified. This can be done with a diode, or alternatively it can be done with a triode by using the lower bend of the mutual characteristic,



(*a*) Input voltage applied to grid (modulated radio frequency)—time plotted vertically downwards; (*b*) output current between anode and cathode—time plotted horizontally.

Fig. 23 Triode as detector. Variations in mean output current correspond to variations in amplitude of input

JKL in Fig. 23. The input voltage is applied to the circuit shown in Fig. 24 between cathode and grid, Y and X. In Fig. 23 this input voltage is shown at (*a*) and the corresponding anode current is shown at (*b*). The mean potential difference between cathode and grid is made to correspond to K so that the voltage fluctuates about a value which lies on the lower bend of the characteristic. It will be seen that the variations in output current are much greater when the voltage changes from K to L than when it changes

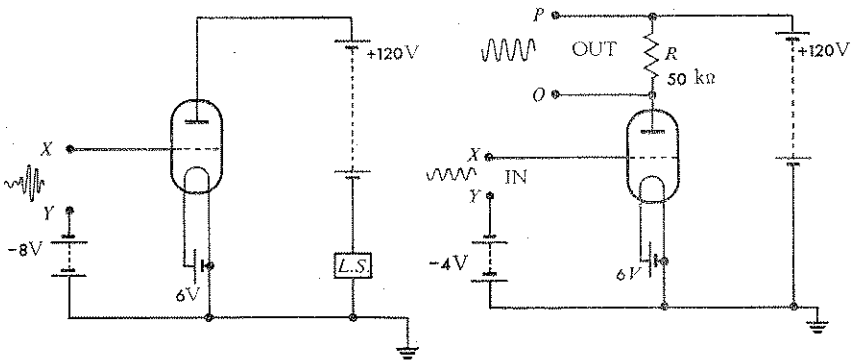


Fig. 24 (left). Triode as detector. Modulated radio frequency applied between X and Y is rectified, and loudspeaker LS responds to mean current which varies with audio frequency.
Fig. 25 (right). Triode as amplifier. Small variations in input voltage between X and Y produce large variations in output voltage, $= RI_A$ *between O and P*

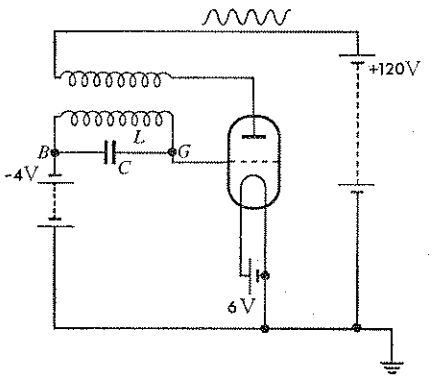


Fig. 26 Triode as oscillator. Output from anode is fed back to grid circuit

from K to J, so that the input voltage variations will cause the current variations to be asymmetrical, thereby producing partial rectification, and the mean current will follow the audio frequency at the transmitter which modulated the wave. This is known as *anode bend detection*. The mean anode potential is usually of the order of a few hundred volts to enable negative potentials to be used for the grid, because if the grid became positive it would collect electrons and this would result in distortion of the output. The mean grid potential is controlled by a *grid bias* supply of about −8 volts, connected in series with the applied alternating potential as shown in Fig. 24. The anode current is sent through the loudspeaker, L.S.,

or earpiece which is connected between anode and cathode, on the *earthed* side of the high tension supply, otherwise the listener would receive a shock when he touched the speaker—this is particularly important if an earpiece is used!

11 Triode as an amplifier

An amplifier is required to increase the amplitude of voltage fluctuations. For this purpose the circuit shown in Fig. 25 is used. It is essentially similar to that employed for detection, but the grid bias is adjusted to about -4 volts, so that the triode is operated on the straight part (LM) of the mutual characteristic (Fig. 23). The anode current is sent through a high resistance, R, of several thousand ohms, and the output is taken from between O and P which are connected to the ends of R, so that a potential difference of RI_A will be developed between them. Small voltage fluctuations applied to the grid between X and Y will therefore result in much larger voltage fluctuations between O and P, and because there is a linear relationship between the output voltage, RI_A, and the input voltage, V_G, the output will be an exact reproduction of the input and will not be distorted. The output is generally made to be 30 to 50 times greater than the input by suitable choice of components, and this can be fed to another triode for further amplification if desired. The additional energy required for the increased output is taken from the high tension supply connected to the anode.

12 Triode as an oscillator

The triode can be used, in conjunction with a 'tuned circuit', as an oscillator to generate an alternating current of high frequency, such as that used for a carrier wave (Fig. 22*a*).

The tuned circuit consists of a condenser C placed across an inductance coil L which is connected to the grid of the triode as shown in Fig. 26. After the condenser is charged, e.g. by switching on the grid bias supply, it will discharge by sending a brief current through the coil L; as the current begins to die down, the self-inductance of L results in an e.m.f. being developed across the coil which makes the current continue to flow, and this charges the condenser in the reverse direction. The whole process is then repeated with the current flowing in the opposite direction. An alternating current will therefore be developed in the circuit, so that G becomes alternately positive and negative relative to B, with a frequency determined by the sizes of the inductance and condenser, ($f = 1/2\pi\sqrt{LC}$). Such oscillations would die down as a result of small energy losses in heating the wires in the tuned circuit if it were not for the action of the triode.

The anode circuit of the triode is 'coupled' to the grid circuit by means of

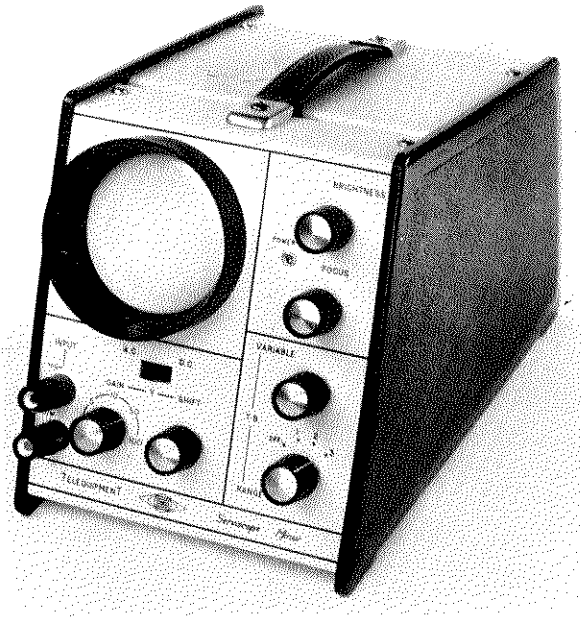
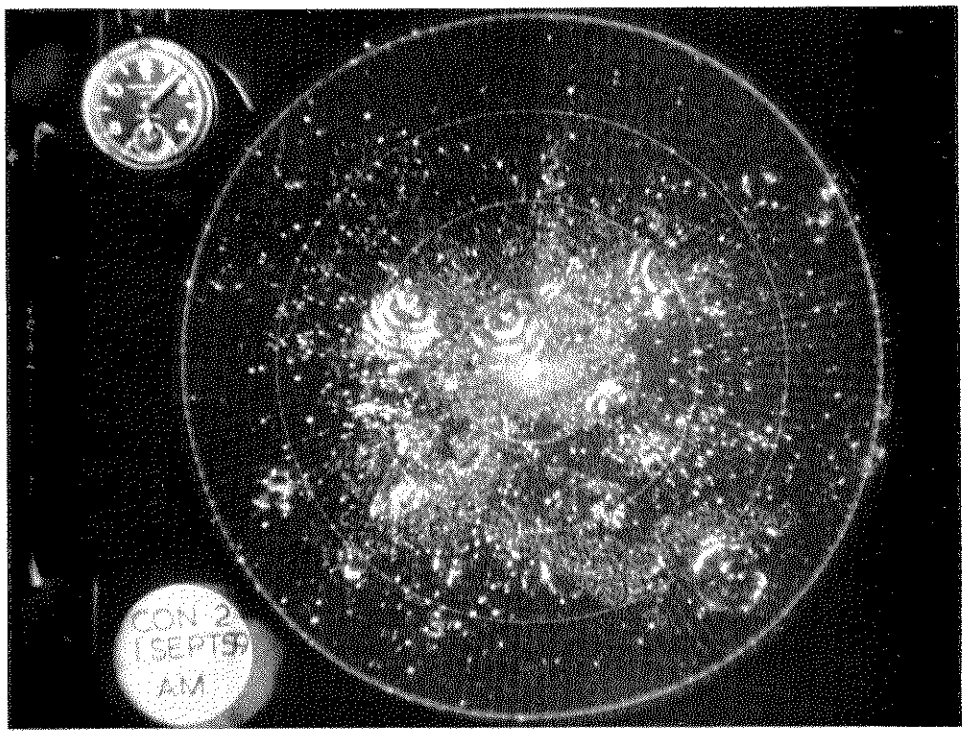


Plate 1 Cathode ray oscilloscope (p. 68).

Plate 2 Radar display showing the positions of birds taken at sunrise on 1 September 1959. Concentric rings show groups of starlings dispersing from their roosts. (Outer calibration circle had a diameter of eighty miles) (p. 72).



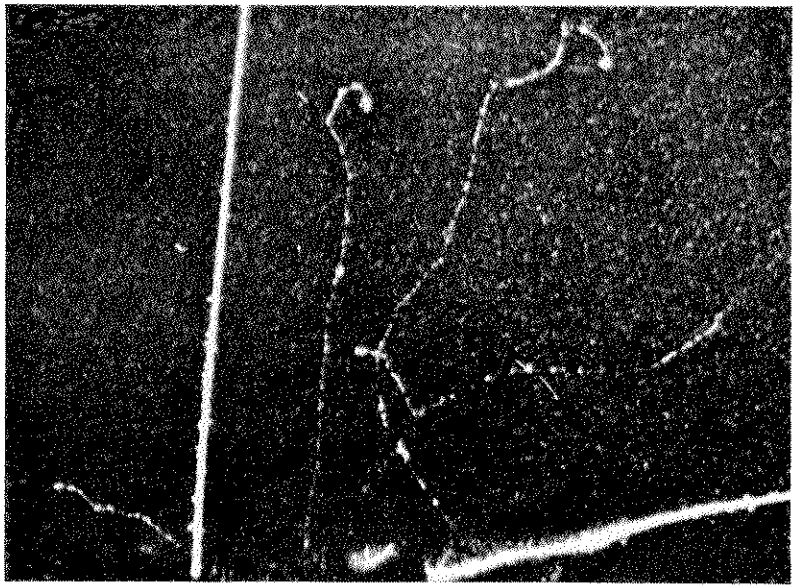
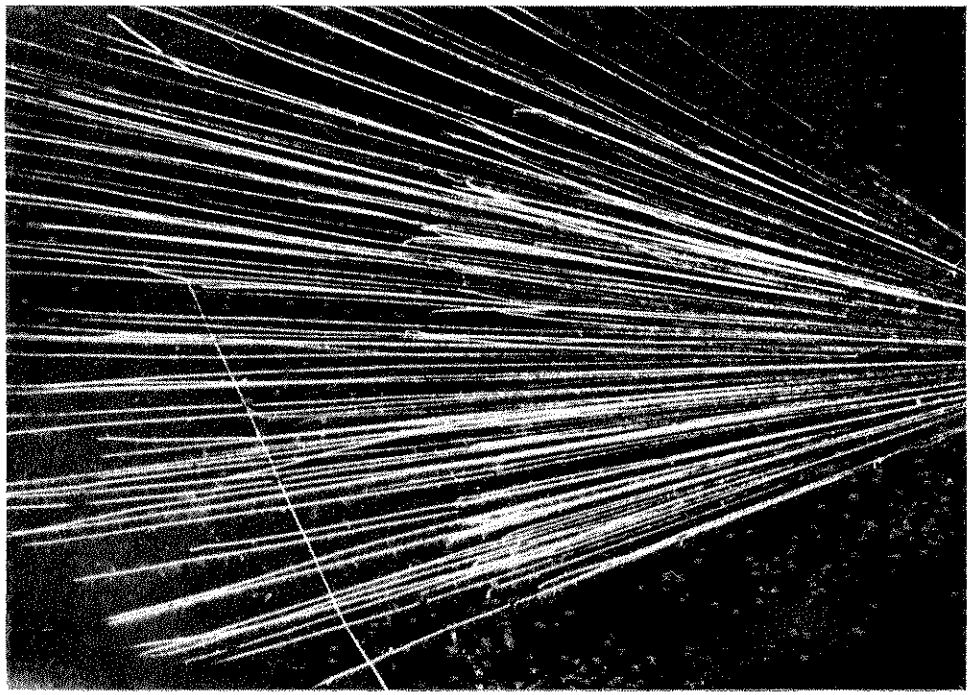


Plate 3 Tracks of alpha and beta particles in a cloud chamber. Thick straight tracks are caused by alpha particles and thin tortuous tracks are caused by beta particles (electrons, which are more easily deflected). These tracks indicate the difference in ionising powers of alpha and beta particles (p. 107).

Plate 4 Tracks of alpha particles in a cloud chamber showing particles emitted with two distinct energies (p. 107). The track not coming from the main source originated from a nitrogen atom which had been ionised by collision with an alpha particle (p. 107).



a transformer of which the inductance, L, forms one coil. An increase in grid potential will increase the anode current, and if the transformer coils are wound in an appropriate direction, this can induce an e.m.f. in the grid inductance, L, which will raise the grid potential still further, and hence further increase the anode current; thus the increase in anode current is cumulative. When the grid potential begins to decrease, then the effect will again be cumulative but in the reverse direction. Thus an alternating current in the grid circuit generates an alternating current in the anode circuit of frequency controlled by the tuned circuit connected to the grid; the amplitude depends largely upon the drop in grid potential, which will cut off the anode current (J in Fig. 23), and not upon the amplitude of the current in the grid circuit. The energy required for the oscillating current in the anode circuit is drawn from the high tension supply to which the anode is connected.

The drop in grid potential which controls the amplitude of the oscillations can be varied by varying the mean potential of the grid, and hence an audio frequency signal applied as voltage variations to the grid will modulate the amplitude of the alternating current in the manner shown in Fig. 22*c*, and in this way the audio frequency message can be transmitted by the radio waves.

13 Valves used in radio

It will be seen that the performance of a diode or a triode valve depends very critically upon the potential of the cathode relative to the other electrodes. For battery operated sets the voltage of the heating current can be accurately controlled so that directly heated cathodes as described above can be used. When the mains is used for operating a set, however, the fluctuations in the heating voltage can cause unwanted variations, so that an *indirectly heated cathode* is generally used. This may consist of a narrow, hollow nickel cylinder, coated with a mixture of barium and strontium oxides, which emits electrons at comparatively low temperatures and which is heated by radiation from a red hot tungsten filament passing up the inside. Such a valve takes a few moments to warm up after the set has been switched on, whereas a directly heated valve warms up immediately.

When high frequency currents are passed through a triode it is sometimes found that the capacitance between anode and grid provides 'feedback', and this can make the valve generate oscillations which are undesirable. The effect is greatly reduced by inserting a fourth and a fifth electrode of which the latter is earthed, between the grid and anode; this type of valve has characteristics which resemble those of a triode in many respects, but it can produce a much greater amplification. It is known as a *pentode*

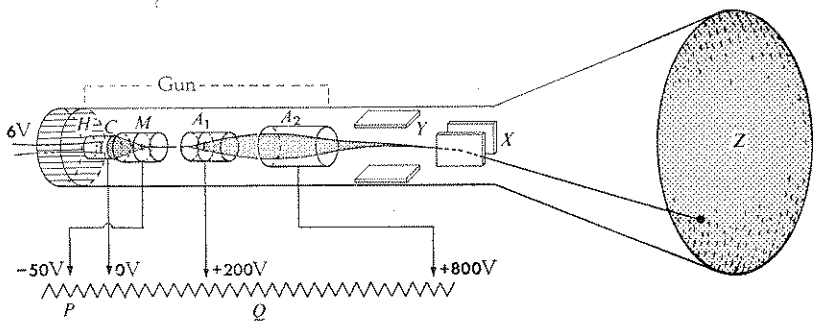
and it has largely replaced the triode in most modern radio receivers in which thermionic valves are used.

THE CATHODE RAY TUBE

A cathode ray tube is familiar to us in a television receiver and also in an oscilloscope, which has become a standard piece of laboratory equipment because of the diversity of uses to which it can be put.

14 Construction of cathode ray tube

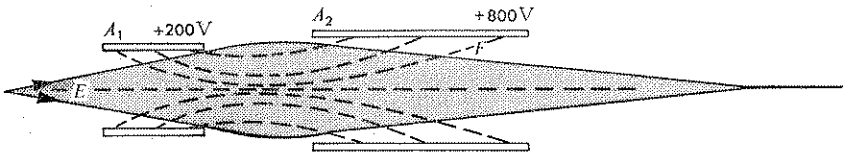
The main features of a cathode ray tube are incorporated in Thomson's apparatus for measuring the specific charge of an electron (Fig. 8, page 41) —a narrow beam of electrons in an evacuated tube is accelerated by a positively charged anode, is deflected by a suitable field and then produces fluorescence on a zinc sulphide screen at the end of the tube.



A_1, A_2, anodes; C, cathode; H, heater; M, modulator (grid); P, brightness control; Q, focus control; X, 'horizontal' deflecting plates; Y, 'vertical' deflecting plates; Z, fluorescent screen.

Fig. 27 Modern cathode ray tube

In a modern tube, illustrated in Fig. 27, electrons emitted from a hot cathode, C, are made to converge to a small spot on the screen by means of electrodes whose potentials enable the size and brightness of the spot to be adjusted. The cathode is indirectly heated as described in section **13**. Immediately in front of it is a cylindrical electrode, M, called the *modulator* or *grid* which is at a negative potential relative to the cathode, and, like the grid of a triode, its potential will have a strong influence on the *number* of electrons emitted because of its proximity to the cathode; it therefore serves as a BRIGHTNESS control. The shape of the electron beam is controlled mainly by means of two cylindrical anodes, A_1 and A_2, maintained at



A_1, A_2, cylindrical anodes; E, electron beam; F, electric field (broken lines).

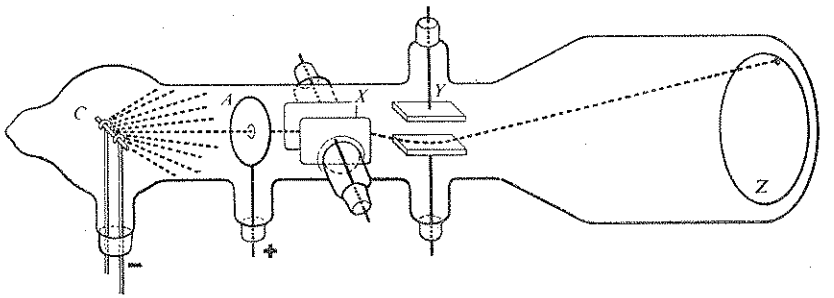
Fig. 28 Electrostatic lens—to focus electron beam

different potentials, the field between which acts on the beam in a manner analogous to a lens for a light beam; the anodes form an electric field shaped as shown in Fig. 28 by the broken lines, and this exerts a force on the electrons which makes them converge; the point of convergence is governed by the potential of the first anode which can therefore be used as a FOCUS control producing a sharp spot of light on the screen. The apertures in the various electrodes are designed to improve the focusing. The cathode, moderator, and anodes are collectively known as the *electron gun*.

The electron beam passes between two pairs of plates and then impinges upon the fluorescent screen Z where it produces a fluorescent spot of light.

The first pair of these plates is mounted horizontally and when a potential difference is applied between them the beam is deflected in a *vertical* direction so that they are known as the Y-plates, and a second pair which can deflect the beam in a horizontal direction is known as the X-plates; thus by suitable potential differences between the X-plates and the Y-plates the fluorescent spot can be deflected to any position on the screen.

All the essential features of a cathode ray tube are clearly seen in Fig. 29 which depicts a very early model dating from the year 1904. Electrons originate from a directly heated cathode C and some of them pass through a small hole in the anode A thereby forming a narrow beam. The beam then



A, anode; *C*, directly heated cathode; *X*, 'horizontal' deflecting plates.
Fig. 29 Simple cathode ray tube (Wehnelt, 1904).

passes between X- and Y-plates and thence to the fluorescent screen Z. The position of the spot can therefore be controlled but its brightness and focusing are not easily adjustable.

15 Cathode ray oscilloscope

A cathode ray oscilloscope is shown in Plate 1. It is a self-contained unit usually run off the mains, incorporating a cathode ray tube and circuits to provide (*a*) suitable potentials for the electrodes in the electron gun, (*b*) amplifier circuits connected to the Y-plates so that very small alternating voltages can produce appreciable deflections of the beam, and (*c*) a time base circuit, as described below, connected to the X-plates, which enables waveforms to be displayed.

A *time base* potential increases steadily and then drops rapidly to zero as shown in Fig. 30, and when applied to the X-plates the spot of light will move steadily to the right and then jump sharply back to the left, moving in a similar way to the eye reading the same line of print over and over again. A simple circuit which will give an approximation to this 'saw-tooth' potential is shown in Fig. 31. The condenser C is charged up slowly through a large resistance so that the potential at X increases steadily. This potential is also applied to one side of a neon flash bulb W and when it reaches a certain value the neon becomes ionised and allows a large current to pass thereby discharging the condenser rapidly, making the potential at X drop

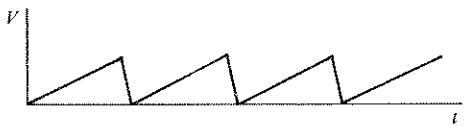
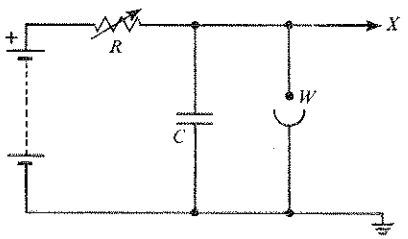


Fig. 30 Saw-tooth voltage for time-base



C, condenser—selected by switch marked RANGE; R, variable resistance—VARIABLE control; W, neon flash bulb, which conducts only when its potential difference is greater than some critical value; X, to X-plates of cathode ray tube.

Fig. 31 Time base circuit

to zero. When the discharge ceases, the neon ions recombine and insulating properties are restored until the critical potential is again reached, when the whole process is repeated. The speed at which the potential increases depends upon the size of the condenser, which can be selected by a switch marked T.B. RANGE, and also upon the resistance which can be adjusted by a control marked T.B. VARIABLE. Thus the rate of sweep of the time base can be adjusted by these two controls, and it can be varied between wide limits, typically from 10 per second to 10^4 per second. A much more sophisticated circuit than that described above is normally used in order to improve the regularity of the voltage variations.

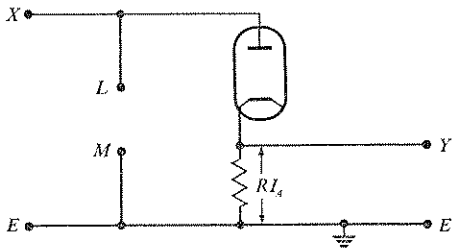
16 Laboratory uses of a cathode ray tube

Waveforms, for example the shape of sound waves, can be inspected using a cathode ray oscilloscope, if the sound waves are converted into electrical voltage variations using a microphone. The microphone is connected via an amplifier to the Y-plates, so that the voltage variations move the spot vertically on the screen. Simultaneously a time base voltage is applied to the X-plates to make the spot move *steadily* in a horizontal direction. The resultant displacements of the spot will therefore be such that a curve is drawn out on the screen which represents the voltage variations from the sound waves plotted against time. The RANGE and VARIABLE controls are adjusted until the time of sweep of the time base is a small integral multiple of the period of the sound vibrations, and in this way the curve will be traced out repeatedly in the same position so that a steady picture of the waveform is displayed.

An oscilloscope can be used as a versatile voltmeter for measuring both direct and alternating voltages. The time base circuit can be disconnected and the unknown voltage compared with a standard by connecting each in turn across one pair of plates and comparing the corresponding deflections. If an alternating voltage is applied then the spot will be drawn out into a line whose length will be proportional to the peak-to-peak voltage. In practice the time base circuit is usually retained so that the voltages are measured by the displacement of a horizontal line which is easier to observe than the displacement of a small spot. The actual displacement for a given voltage depends upon the separation of the plates, and since the Y-plate separation is usually different from that of the X-plates, the sensitivity of the voltage measurements will depend upon which pair is used. The oscilloscope has several advantages over the more conventional type of voltmeter: it takes no current and so does not disturb the circuit in which measurements are being taken; it cannot be damaged by overloading, as this would merely cause the spot to go off the screen; it can be used either

for alternating or direct current; and it can be used for very small alternating voltages by utilising the amplifier circuits incorporated in it. It should be noted that for a.c. measurements the peak-to-peak voltage is obtained, and not the root mean square voltage which is measured by most voltmeters.

A third laboratory use for an oscilloscope is to display curves, such as a valve characteristic or a magnetic hysteresis loop. The two quantities to be 'plotted' are applied to the appropriate plates; for example the dynamic characteristic current : voltage of a diode can be displayed using the circuit shown in Fig. 32.



L, M terminals for alternating input voltage; X, Y, E to oscilloscope terminals: X-plates, Y-plates, earth.

Fig. 32 Circuit for diode characteristic using cathode ray oscilloscope. X-deflection shows input voltage V_A. *Y-deflection shows output current* I_A

The X-plates are connected between anode and cathode across which an alternating voltage is applied, and the output current passes through a large resistance, R, developing a potential difference across it equal to RI_A which is applied between the Y-plates. Thus the horizontal displacement is proportional to the voltage applied to the diode and the vertical displacement is proportional to the current.

17 Television receiver

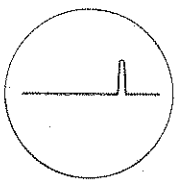
The most familiar application of a cathode ray tube is probably a television receiver. For this purpose the beam is made to scan the screen in the same way that the eye scans a book when reading a whole page. This is accomplished by applying a rapid saw-tooth voltage to the X-plates and a slower one to the Y-plates, so that 625 lines are drawn across the tube, one below another, for each picture, and this is repeated twenty-five times a second. The modulator is biased by the BRIGHTNESS control in such a way that the electron beam is prevented from reaching the screen until an additional signal comes from the transmitter. The camera at the transmitter scans an

image of the scene to be televised and sends an additional current when pointing to a bright area (see p. 196). The scanning at the receiver is synchronised with that at the transmitter and the additional current produced when the camera points to a light area causes an additional potential to be applied to the modulator at the receiver, thereby enabling the electrons to reach the screen and make it fluoresce.

18 Radar

Radar signals are displayed using a cathode ray tube. One of the original forms of radar was used at anti-aircraft gun sites during World War II to track enemy aircraft. Brief pulses of electromagnetic radiation, a few centimetres in wavelength, were sent out in a direction controlled by the aerials and if they struck a target they were reflected back to the receiver where they were made to produce a vertical deflection on the screen (Fig. 33). The start of the time base was synchronised with the emission of the radar pulse so that the vertical deflection appeared in a position which depended upon the time interval that had elapsed between sending the pulse and receiving the reflection, and hence upon the distance of the target. The direction of the target was given by the direction of the aerials when the reflection was received.

In most modern radar displays the tube is biased by the modulator potential in the same way as for television reception so that no spot is obtained on the screen unless a reflection is received. The time base starts from the centre of the tube and its direction follows that of the aerial and therefore indicates the direction of the target when a reflection is received (Fig. 34). Hence a bright spot appears at a distance from the centre of the screen corresponding to the distance of the target and in a direction corre-



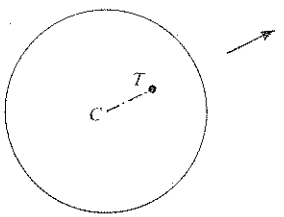


Fig. 33 (left) Radar display used for gun-laying during World WarII—distance of pulse from start of line measures distance of target

C, centre of screen; T, bright spot, produced by reflection from target, whose position on screen indicates position of target.

Fig. 34 (right) Modern radar display. Direction of CT gives direction of beam radiated by aerial. Distance CT gives distance of target

sponding to the direction of the target, so that the screen shows a 'map' of all the reflecting targets as the aerial rotates.

A radar display of this type, showing individual birds is given in Plate 2; this display was observed at sunrise and the concentric rings show groups of starlings dispersing from their roosts.

Problems on Chapter Three

1. Give an account of the emission of electrons from heated surfaces in vacuo. Explain the terms *space charge* and *saturation*.

Describe the structure of a diode valve and explain the action of *either* (*a*) a half wave diode rectifier *or* (*b*) a full wave diode rectifier.

L W63 II–11

2. Describe in detail the structure and characteristics of the diode valve.

How may these valves be used to produce (*a*) half wave, (*b*) full wave, rectification of an a.c. supply? S 60 II–4

3. Give an account of the thermionic diode, explaining carefully the terms *thermionic emission*, *space charge*, and *saturation current*.

How would you use a diode and other necessary apparatus to obtain a reasonably steady unidirectional voltage from an alternating supply?

O 60 II–12

4. Give an account of the thermionic diode, and describe how you would investigate the way in which the current through the diode depends on the power supplied to the heater.

Explain the use of the diode as a rectifier of alternating current. Draw a diagram of one type of rectifier-smoother circuit which will give an essentially steady direct voltage from 50-cycle alternating mains, and explain the function of each component in the circuit. O Sp. 62 IV–11

5. Describe in detail the construction, characteristics, and action of (*a*) a diode used as a rectifier, (*b*) a triode used as a voltage amplifier.

S 62 II–9

6. Describe the structure of a diode and describe an experiment to justify the term 'valve'.

Explain how a triode (*a*) differs in structure and operation from a diode, (*b*) may be used to amplify small alternating potential differences.

L 64 II–11

7. Draw and label a diagram showing the essential features of a triode valve.

Describe an experiment to determine the form of the anode current/grid voltage characteristics of such a valve, and discuss the form of these curves.

Explain the principles of amplification of alternating voltage signals

using a triode valve, and mention the factors on which the magnitude and faithfulness of the amplification depend. L 60A II–12

8. Draw a labelled diagram showing the circuit required to determine the anode current in a triode valve with changes in grid potential, for various fixed anode potentials.

Explain how a triode may be employed (*a*) as a detector of radio frequency signals, (*b*) to maintain radio frequency oscillations of a desired frequency. L 64A II–10

9. For a triode sketch curves to show (*a*) the form of the anode current/grid voltage static characteristics, (b) the form of the anode current/anode voltage static characteristics. How may the amplification factor of the valve be deduced from these curves?

Explain, with the aid of a circuit diagram and with reference to the static characteristics, how the triode may be used to amplify a small alternating voltage. N 64A II–12

10. Describe the structure and mode of action of a triode valve. How would you investigate experimentally the variation of the anode current with the grid voltage?

For a certain triode the anode currents I_1 and I_2 in milliamps, for anode potentials of 100 volts and 130 volts respectively, vary with the grid voltage V_g as follows:

V_g	0	−2	−4	−6	−8	−10
I_1	10	8	6	4	2	0·8
I_2	15	13	11	9	7	5

Plot the anode current/grid voltage characteristic curves and hence determine, for a grid voltage of −3·5 volts, (*a*) the anode resistance, (*b*) the mutual conductance, and (*c*) the amplification factor of the valve.

N 64B II–10

11. Describe, with the aid of a circuit diagram, how you would obtain a set of mutual characteristics for a triode valve. Explain how you would use these curves to calculate the mutual conductance g, the impedance r, and the amplification factor μ of the triode.

Discuss the action of the triode as an amplifier of small voltage changes.

O Sp. 61 I–12

Cathode ray oscilloscope

12. Give a short account of the conductivity of electricity through gases, discussing both ionised gases at ordinary pressures and also discharge tube conditions.

Describe the cathode ray tube. Give an account of one method of deflecting the cathode ray beam, and describe how the brilliance and focusing of the cathode ray beam may be controlled. O 60 I–12

13. Draw a sketch to show the essential parts of a cathode ray oscillograph having electrostatic deflection.

With the help of your sketch explain how in a cathode ray oscillograph (*a*) the electrons are produced, (*b*) the electrons are focused, (*c*) the spot is made visible, and (*d*) the brightness of the spot is controlled.

What is meant by stating that a cathode ray oscillograph is fitted with a linear time base of variable frequency? N 65 I–14

14. Write an essay on the cathode ray oscilloscope and its applications. L 63A II–12

15. Describe an experiment to determine the charge of the electron. Explain how the result is derived from the experimental observations.

If the charge of the electron were to be doubled, how would the deflection sensitivity of a cathode ray oscilloscope be affected? Give reasons for your answer. N 63 II–12

16. Describe the apparatus required to produce a well-defined beam of fast moving electrons.

A beam of electrons accelerated from rest through a potential difference of 5·0 kilovolts passes between a pair of parallel deflecting plates 0·50 cm apart. A uniform magnetic field of 25 oersted acts in the region between the plates, the lines of force being parallel to the plates and perpendicular to the beam. What potential difference must be applied between the plates so that the beam is not deflected? (Assume e/m for electrons to be $1{\cdot}76 \times 10^7$ e.m.u. g^{-1}.) L 64A II–11

17. Give an account of the structure and mode of operation of a cathode ray oscilloscope. (Details of the time base are *not* required.)

Describe briefly *one* application other than the measurement of potential difference, not necessarily requiring the use of a time base.

Electrons in a cathode ray tube are accelerated through a potential difference of 300 volts and the axis of the tube is placed at right-angles to the magnetic meridian.

Find how the earth's magnetic field will affect the position of the spot on the screen, if the axial distance between anode and screen is 20·0 cm and the induction of the earth's magnetic field is 0·650 gauss. (e/m for an electron $= 1{\cdot}76 \times 10^7$ e.m.u. g^{-1}.) L Sp. 62–12

Chapter Four

Sub-atomic Particles and Positive Ions

1 Proton

A *proton*, as we saw in Chapter One, is a constituent of all atoms. The number of protons in a nucleus is equal to its atomic number, Z, and it determines the chemical element of the atom. Since hydrogen has an atomic number of one and a mass number of one, its nucleus must consist of a single proton, so that a proton can be described as a hydrogen nucleus.

The electric charge of a proton is positive and it exactly neutralises that of an electron so that its charge $= +1{\cdot}602 \times 10^{-19}$ coulomb.

In early measurements, the mass of a proton was taken as the unit for atomic mass, but the atomic mass unit is now defined in terms of the carbon-12 atom (see p. 28). The mass of a proton can be measured accurately using a mass spectrograph and is found to be equal to 1·0073 a.m.u.

Protons, like electrons, can pass through small thicknesses of solid materials, and as they do so they cause fairly intense ionisation by attracting electrons away from the outer orbits of atoms; this makes protons lose energy fairly rapidly and their powers of penetration are smaller than those of electrons. Their ionisation tracks are similar to those of alpha particles shown in Plate 3.

When a proton spins on its own axis it acquires a magnetic moment. Although the effect is very small, it is sufficient for spinning protons to be used as an extremely sensitive magnetometer by measuring the frequency at which the magnetic axes of the protons precess round the magnetic field. A proton magnetometer can measure changes in the earth's field of a millionth of a gauss and it has been used by archaeologists to locate ancient pits, since the disturbance of the earth when the pit was dug alters its permanent magnetism, and hence the neighbouring magnetic field to a degree that is detectable by a proton magnetometer.†

2 Neutron

A third constituent of all atoms (except hydrogen-1) is a *neutron*. It has a mass which is slightly greater than that of a proton, being 1·0086 a.m.u. and it is electrically neutral. Neutrons therefore add to the mass of an atom without influencing its electric charge. They do not affect the chemical properties of the atom, but they do affect the stability of certain nuclei and

† See PHYSICS AND ARCHAEOLOGY, M. J. Aitken, Wiley, 1961.

Chapter Five

Properties of Radioactivity

1 Distribution of positive charge in an atom

The theory in its modern form that all matter is composed of atoms dates from 1803 when John Dalton put the atomic theory of chemical combinations on a firm numerical basis by weighing accurately with the aid of the newly invented chemical balance. His conception of an atom was that of a solid uniform lump like a billiard ball.

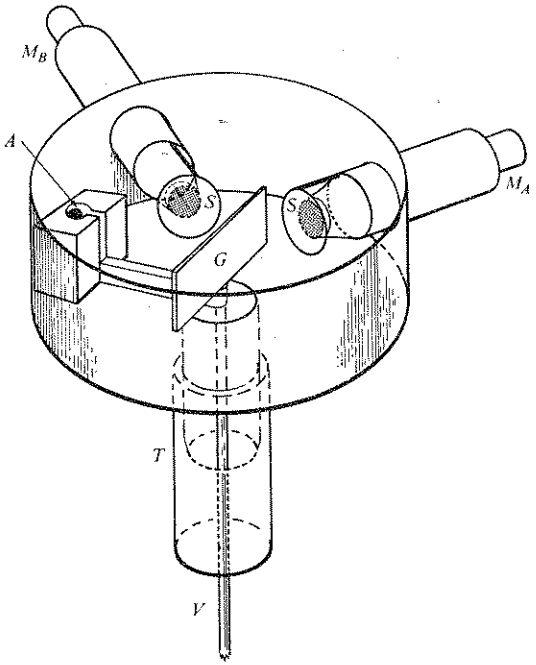
Thomson's experiments of 1895 using low pressure discharge tubes showed that electrons can be released from the atoms of a great many materials in the form of cathode rays. They can also be extracted by other processes such as thermionic emission and photo-electric emission in which electrons are released when light falls on certain materials (see p. 192). This suggests that electrons are incorporated in the atoms of which matter is composed. Since matter as a whole is neutral, atoms must also contain positive electricity; experimental evidence in support of this is supplied by the positive rays in a discharge tube which originate from the atoms in the gas (p. 77). The way in which this positive charge is distributed in an atom will now be considered.

The positive charge could be evenly distributed throughout the atom, together with the negative charge, like the ingredients of a plum pudding. Another possibility is that all the positive charge is confined to a small part of the atom, giving a picture of an atom which may be described as a nuclear model. These possible models are illustrated in Fig. 79. An experiment to select the most probable model was first carried out in 1911.

2 Evidence for a small nucleus—Rutherford's α particle scattering

The choice between the billiard ball, plum pudding, or nuclear models of the atom was made as a result of an experiment suggested by Rutherford using the apparatus shown in Fig. 37.

Thin gold foil was bombarded with alpha particles. Alpha particles are helium nuclei and are emitted spontaneously by radium; they are suitable for this experiment because they are small enough to penetrate into the interior of an atom and because they carry a positive charge, and so will be deflected if they approach another charge. They cause zinc sulphide to fluoresce if they impinge upon it, each alpha particle producing a separate flash of light which may be seen with the aid of a microscope. In Rutherford's apparatus (Fig. 37) a small zinc sulphide screen S is fixed in front of

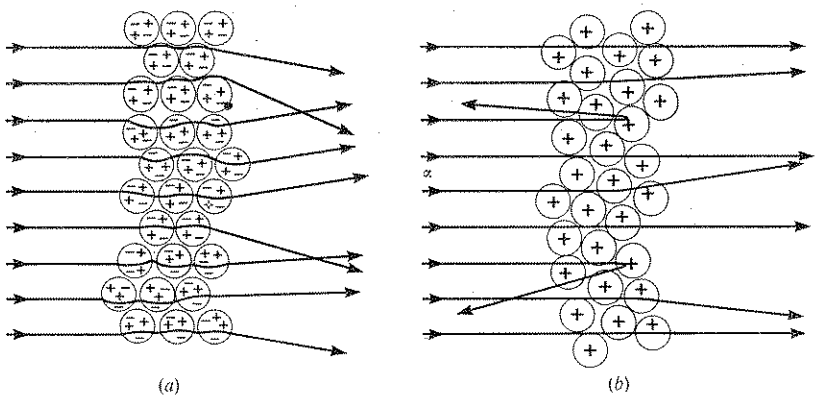


A, alpha particle source (radium in lead shield); G, gold foil which scatters particles; M_A, microscope—position A; M_B, microscope—position B; S, fluorescent screen; T, air-tight joint; V, connection to vacuum pump.

Fig. 37 Rutherford's alpha particle scattering experiment for demonstrating small size of nucleus—a few particles are deflected through a large angle and are received by the microscope when in position M_B

a microscope M to detect the particles. The radium source A and the gold foil G are fixed in position while the microscope with the fluorescent screen is attached to the walls of the chamber which may be rotated in an air-tight joint T, and the whole chamber is evacuated in order to allow the alpha particles to move freely.

If the gold atoms were completely solid, like billiard balls, then no alpha particles would penetrate to the other side of the foil so that no scintillations would be observed when the miscroscope was in position M_A. If they were like the plum pudding model, with positive and negative charges evenly distributed in the atom, then the effects of the charges in the atoms would largely cancel each other out so that alpha particles would be deviated only slightly and none would be received in position M_B, this condition is illustrated in Fig. 38*a*.



(*a*) Plum pudding model—small deviation of alpha particles expected; (*b*) Nuclear model—if positive charge is concentrated in a small nucleus, some alpha particles would be scattered through large angles.

Fig. 38 Deviation of alpha particles to be expected in Rutherford's experiment

It was found, however, that although most of the alpha particles were deviated to only a small extent, a significant number were scattered through large angles, or even turned backwards and were observed by a microscope in position M_B of Fig. 37. This can be explained, as illustrated in Fig. 38*b*, if the positive charge in the gold atom is concentrated into a very small space, which we can describe as a nucleus and the electrons are spread out round it so that a positive alpha particle is only strongly deflected if it approaches close to the positive nucleus. In addition, the proportion of alpha particles scattered in this way gives an indication of the volume of the nucleus relative to the whole of the gold atom.

The experiment therefore showed that the nuclear model of the atom is substantially correct, and furthermore, that the positively charged nucleus occupies only about a million millionth part of the volume of the whole atom.

In order to visualise the relative size of the nucleus, imagine an atom to be blown up to the size of a house (a football on this scale would have a radius of a million miles); the outermost electrons would be moving round the walls of the house, but the nucleus would have a diameter of only 1 millimetre. The atom, therefore, is practically all empty space. The nucleus is so small that, if there were no mutual repulsion, the nuclei of all the atoms in the City of London would fit into the space of an egg-cup. A typical nucleus has a diameter of 10^{-12} centimetres, and since almost the entire mass of the atom resides in the nucleus, its density is enormous.

For instance, taking an average atom of mass 100 a.m.u., the density is of the order of half a million tons per cubic millimetre.

But in spite of its small dimensions, the nucleus is all-important in determining both the chemical and the radioactive properties of the atom. We saw in Chapter One that the nucleus is a composite body; the number of protons is equal to the atomic number Z and governs the chemical nature of the atom, while the number of neutrons, equal to $A-Z$ (where A is the mass number), has no effect on the type of chemical element. The numbers of neutrons, however, can have a profound effect on the radioactive behaviour; thus, different isotopes of the same element often possess very different radioactive properties.

3 Isotopes

The number of different *elements* that have been identified is only 103, of which ninety occur in nature and the rest are man-made. But a single element can have several different *isotopes*, so that the total number of different types of atoms far exceeds 103. In fact over 1 300 have so far been identified, of which about 300 occur in nature and the rest have been made artificially. To take one example, the mercury found in natural ores is a mixture of seven different isotopes, and a further fourteen have been produced artificially (see Appendix 3). Many of the naturally occurring isotopes and all the man-made ones have unstable nuclei and as a consequence they eject charged particles spontaneously. This is the phenomenon of radioactivity and the isotopes which exhibit it are often referred to as radioisotopes. The most widely known radioisotope is radium.

4 Stable isotopes

The different isotopes which have been identified are given in Fig. 39 in which the number of neutrons in the nucleus is plotted against the number of protons. The stable nuclei are shown by solid black squares, and all the others are radioactive. It is immediately apparent that for stability there is some kind of correlation between the numbers of protons and neutrons—for light elements the numbers of each type of nucleon is approximately equal, whereas the heavier elements have a preponderance of neutrons. A further point which is apparent from the diagram is that there is a tendency for stable nuclei to have an even number of protons and of neutrons, and this suggests that the nucleus has an internal structure. The details of this structure are not yet fully known, but it seems that a combination of two protons and two neutrons is a particularly stable one—a combination which is ejected in many radioactive disintegrations in the form of alpha particles. The stability inherent in even numbers of protons and neutrons

is further suggested by the abundance among natural ores of the isotopes ${}^{16}_{8}O$, ${}^{28}_{14}Si$ (silicon), and ${}^{56}_{26}Fe$, which together constitute over 80 per cent of the earth's crust. (The lower figure in these symbols gives the atomic number and the upper figure gives the mass number—see p. 27. No distinction is usually made between symbols representing the atom as a whole or the nucleus alone, as the meaning is usually clear from the context.)

5 Unstable isotopes (radioactive isotopes)

Certain materials such as uranium compounds are found to emit rays continuously and these rays can penetrate solid materials and cause fluorescence on a suitable screen, but they have powers of penetration which differ considerably from one another and show that three different types of rays can emanate from naturally occurring radioisotopes. These have been designated alpha (α), beta (β), and gamma (γ) rays. By applying a magnetic field at right-angles to the paths of the rays, it has been shown that alpha rays consist of positively charged particles, beta rays consist of negatively charged particles, while gamma rays are undeflected by the field and have properties associated with electromagnetic waves. The term 'ray' was applied to alpha and beta particles before their true nature was known, and it is still often used (c.f. cathode rays).

Naturally occurring radioisotopes all emit either alpha or beta particles and some also emit gamma rays. Since alpha and beta particles are electrically charged, their emission changes the atomic number Z of the nucleus so that the element must be transformed into a different *element*. The daughter element thus formed will lose or gain orbital electrons from its surroundings so that a neutral atom of the new element will very soon be produced. (This type of change should not be confused with chemical changes among compounds in which the atomic nuclei remain unchanged but the atoms combine with one another in different ways.) The daughter element itself is frequently radioactive, so that a series of radioactive isotopes is produced, such as those shown in Fig. 42 (p. 99).

The type of particle emitted by a nucleus is characteristic of that particular isotope. Referring again to Fig. 39, in which isotopes emitting negatively charged particles are marked by a dot • while those emitting positive particles are marked by a cross + or ×, it will be seen that the particles emitted generally result in the daughter nucleus being nearer to the stable area of the diagram than the parent one, and emission continues until a stable nucleus is formed.

black square = stable nucleus *cross* = alpha particle
black circle = beta particle emitted *open circle* = spontaneous fission
plus-sign = position emitted or electron captured

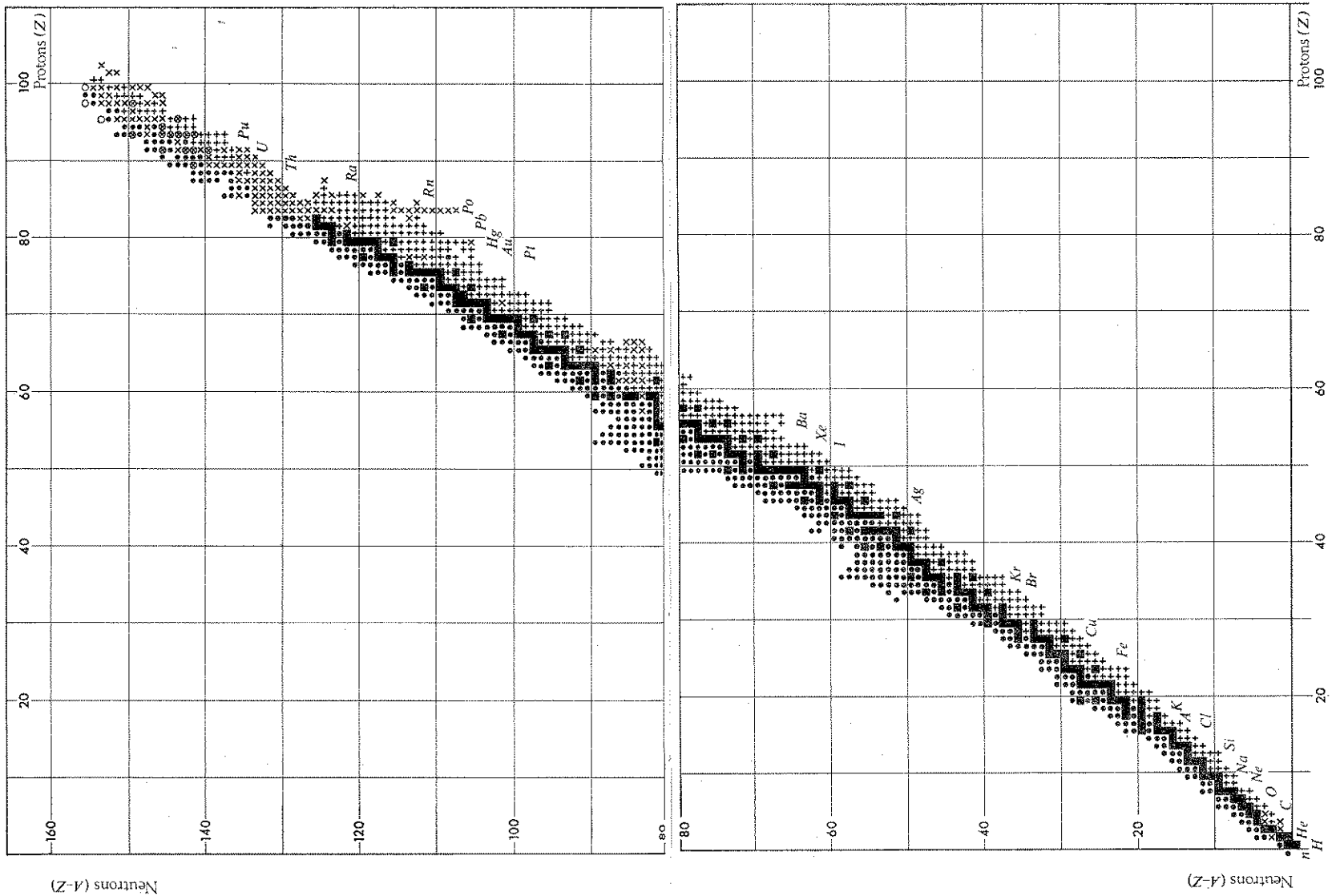


Fig. 39 Isotopes which have been identified. Majority of stable nuclei have even numbers of protons and neutrons

thus the process of natural selection reduces the significance of these mutations.

It should perhaps be emphasised that man-made radiation is only one of several causes of mutations—they are also produced by certain chemicals, of which mustard gas is an example, as well as by natural background radiation to which man has always been subjected.

13 Summary of properties of alpha, beta, and gamma rays

	Alpha rays	Beta rays	Gamma rays
Nature	Helium nuclei (2p + 2n)	Fast electrons	*e-m* waves ($\sim 10^{-9}$ cm)
Charge	++	−	none
Energy on emission	$\frac{1}{2}mu^2$. Characteristic of isotope	$\frac{1}{2}mu^2$. Range of energies whose maximum is characteristic of isotope	$h\nu$. Characteristic of isotope
Penetration of typical rays	5 cm of air, Paper	500 cm of air, 0·5 cm aluminium	50 000 cm of air or 4 cm of lead reduces intensity to $\frac{1}{10}I$
Affect photo plate	yes	yes	yes
Cause fluorescence	yes	yes	yes
Deflected by magnetic field	yes	yes	no
Ionising	strong	appreciable	very little
Path through matter	straight	tortuous	straight
Inverse square law in air	no	no	yes

RADIOACTIVITY

14 Laws of radioactive decay

Radioisotopes vary in the type of radiation they emit (alpha, beta, etc.). They also vary in the energy with which they emit these radiations and in the rate at which the atoms disintegrate.

Radiation from radioactive materials is found to obey the following laws:

a *The emission is characteristic of the isotope*; it varies from one isotope to another of the same element, so that radioactivity must depend upon the number of neutrons as well as the number of protons in the nucleus.

b Radiation occurs spontaneously and *cannot be speeded up or slowed down* by physical means such as change of pressure or temperature.

c *The time taken for half the atoms to disintegrate is constant for a particular isotope*; this period of time is called the *half-life*, $T_{\frac{1}{2}}$. If the half-life is very long then the isotope will change slowly.

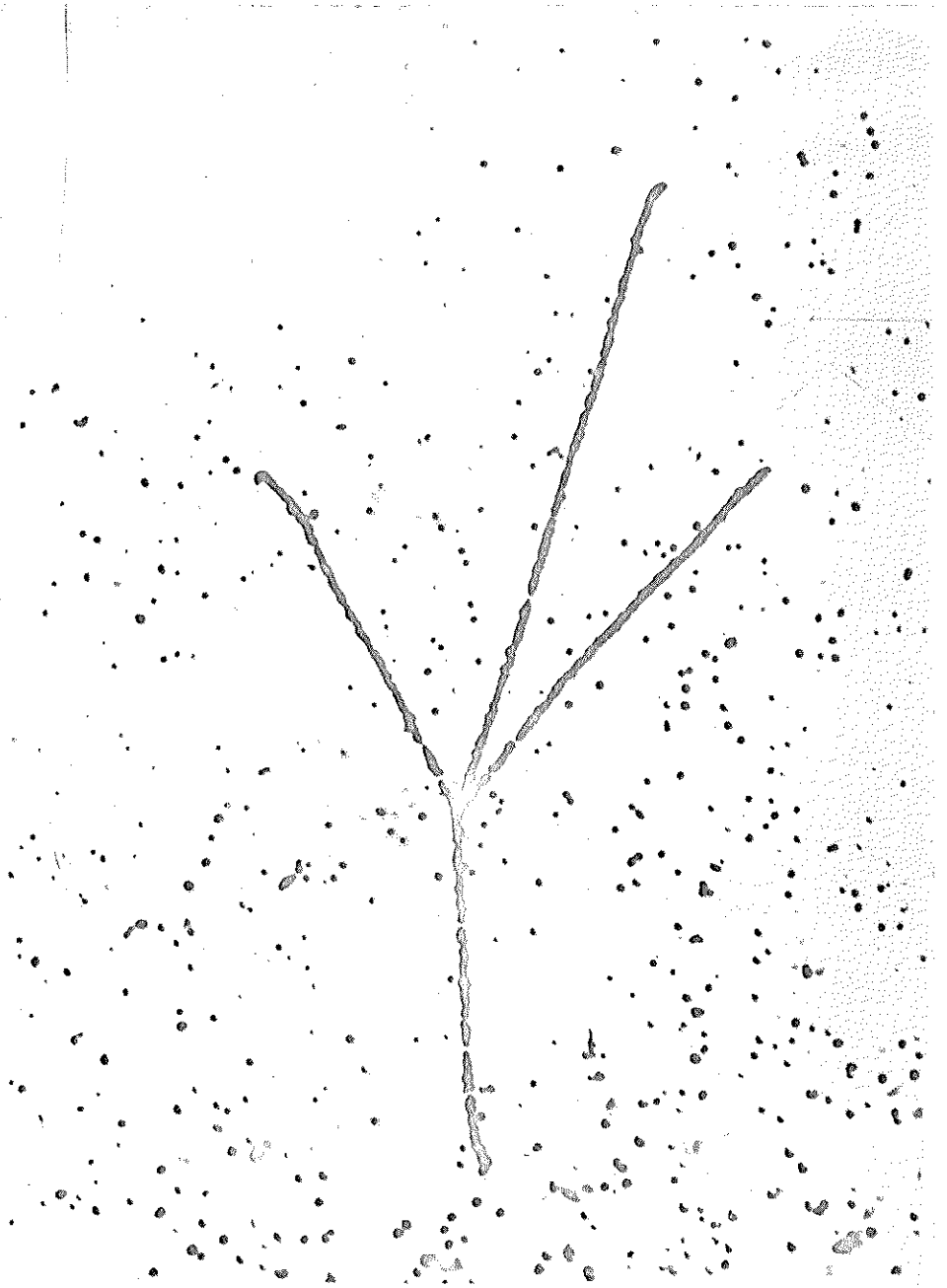
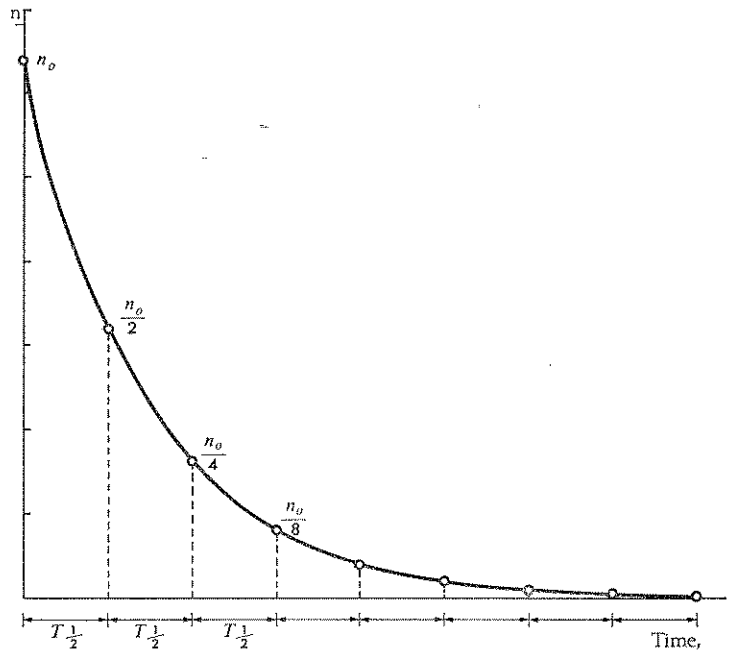


Plate 5 Tracks of alpha particles emitted from a single nucleus. The tracks came from a single nucleus as it changed successively from radium-224, radon-220, and polonium-216; then two beta particles were emitted which left no tracks, then another alpha particle from polonium-212. Tracks are caused by ionisation of the photographic emulsion (p. 100).

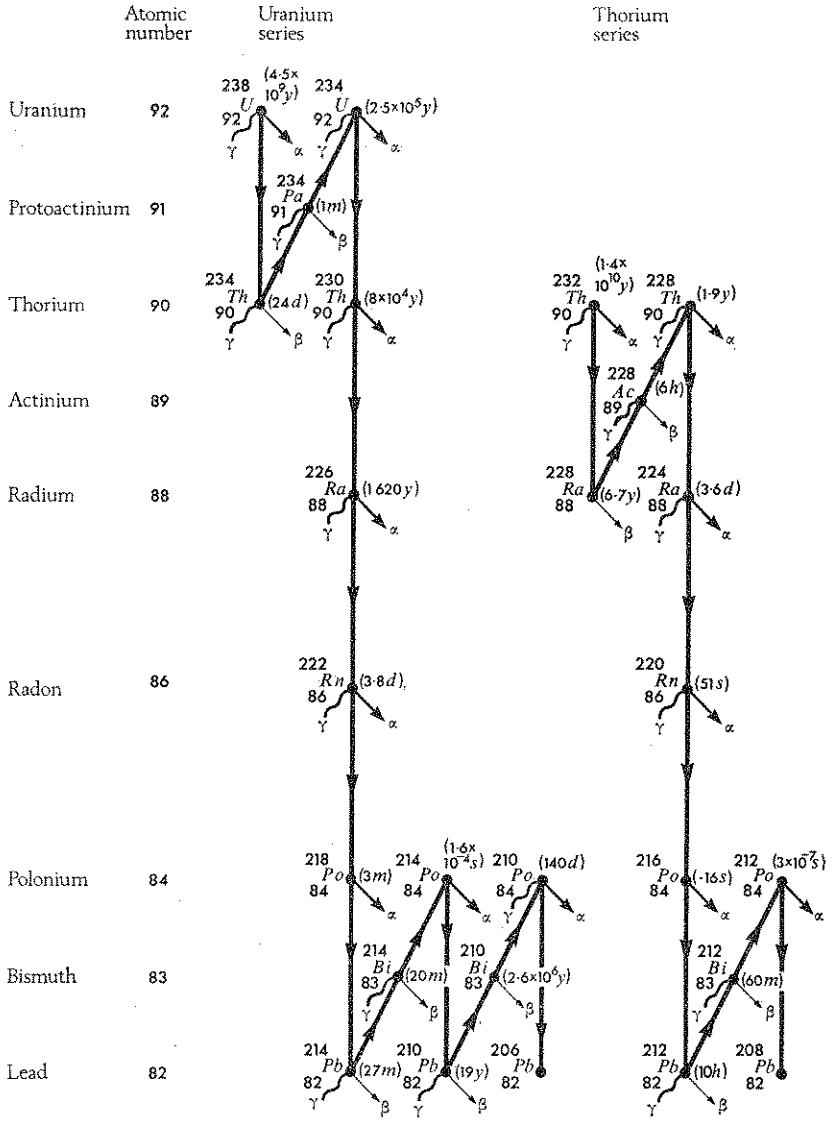


n, number of unchanged atoms: $T_{\frac{1}{2}}$, half-life.

Fig. 41 Decay curve. Time taken for number of unchanged atoms to be halved is always the same, $T_{\frac{1}{2}}$

Thus an isotope with a long half-life has a small decay constant and disintegrates slowly, whereas one with a short half-life has a large decay constant and disintegrates rapidly, i.e. it is very unstable.

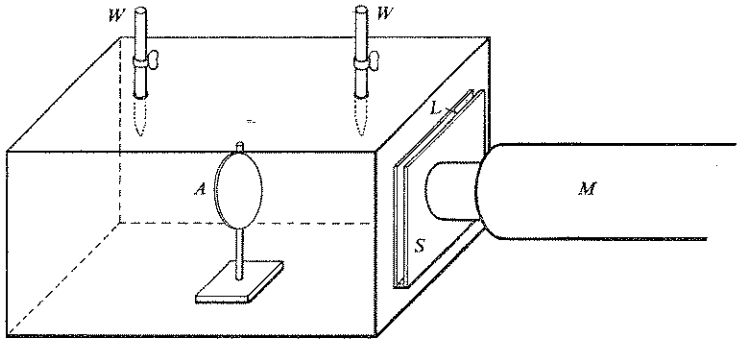
Since the atoms of a radioactive isotope are continually breaking up, the original material will gradually disappear, unless, of course, it is being replaced from some other source as, for example, in the series given in Fig. 42. A graph of the number of atoms remaining after a time t will take the form shown in Fig. 41 which is obtained by plotting at successive time intervals equal to the half-life $T_{\frac{1}{2}}$, the numbers n_0, $\frac{n_0}{2}$, $\frac{n_0}{4}$, $\frac{n_0}{8}$, etc. It will be seen that the number of atoms is never reduced to zero so that the material never disappears completely; it would therefore be meaningless to refer to the 'life' of a radioisotope whereas the 'half-life' has a clearly defined meaning. After ten half-life periods only one part in a thousand will remain



y, years; *d*, days; *h*, hours; *m*, minutes; *s*, seconds.

Fig. 42 Natural radioactive series. Numbers in brackets are half-lives

$\left(\frac{1}{2^{10}} = \frac{1}{1\,024}\right)$, and for practical purposes a radioisotope can usually be assumed to have disappeared after this interval of time.



A, alpha particle source; L, foil to absorb alpha particles; M, microscope; S, fluorescent screen; W, gas inlets.

Fig. 43 Transmutation of nitrogen into oxygen (Rutherford's apparatus) ${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$. *The protons formed penetrated the absorbing foil and produced scintillations. Some oxygen was found in the chamber*

(In an equation of this type, there must be the same number of protons and of neutrons on each side, and therefore there must be a balance in the atomic number Z, which gives the number of protons, and the mass number A, which gives the total number of neutrons plus protons. In the above equation, the alpha particle has been described as a helium nucleus and the proton as a hydrogen nucleus.)

Artificial isotopes are now made on a large scale by leaving materials inside a nuclear reactor where there is an abundance of free neutrons, some of which are likely to be captured by the atomic nuclei, thereby making a different isotope. Sometimes this new isotope is used as it is, but at other times the decay product produced after it has disintegrated is more useful, so that the element produced differs from the original one.

Transmutation of elements can also take place in nature; for example carbon-14 is made continuously in the atmosphere by the bombardment of nitrogen by neutrons, which are always present and originate from cosmic rays and other sources.

${}^{14}_{7}\mathrm{N} + {}^{1}_{0}n \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$, where ${}^{1}_{0}n$ represents a neutron.

A heavy isotope of hydrogen, H-3, is also made in the atmosphere by the bombardment of nitrogen with neutrons but the neutrons have much higher energies than those producing carbon-14:

${}^{14}_{7}\mathrm{N} + {}^{1}_{0}n \xrightarrow{\text{fast}} {}^{12}_{6}\mathrm{C} + {}^{3}_{1}\mathrm{H}$

***20 Artificial radioactivity**

'Artificial' radioactivity refers to radioactivity from isotopes that have been made by nuclear bombardment as described above. The great majority of these isotopes are man-made, but carbon-14 and hydrogen-3 are examples which occur in nature.

Artificial radioactivity follows the same general pattern as natural radioactivity, but in addition to the emission of alpha and beta particles and gamma rays, certain other processes can take place. One of these is the emission of a *positron*, which is a particle similar to an electron but with a positive charge. A further possible process is the capture by a nucleus of one of its own orbital electrons, after which the remaining electrons in the atom redistribute themselves, and in so doing they emit X-rays. Both positron emission and electron capture result in the atomic number of the nucleus decreasing by unity while the mass number remains unchanged. Isotopes which exhibit these two types of radioactivity are marked by + in Fig. 39.

Problems on Chapter Five

1. Define *atomic number* and *mass number* and explain the term *isotope*.

In the decay series of the naturally occurring heavy elements there are several cases in which the nucleus emits an alpha particle followed by two beta particles. Show that the final nucleus is an isotope of the original one and write down the change in mass number. 0 64 II–13 (part)

2. '${}^{24}_{11}\mathrm{Na}$ is a *radioactive isotope* of sodium which has a *half-life period* of 15 hours and disintegrates with the emission of *beta particles* and *gamma rays*. It emits beta particles which have an energy of 4·2 *MeV*.'

Explain the meanings of the five terms italicised in the statement above. L 62 II–12

3. Write brief notes on *three* of the following (*a*) beta particles, (*b*) neutrons (*c*) protons, (*d*) gamma radiation. L W63 II–12 (part)

4. Compare and contrast the properties of α-particles, protons, and neutrons.

Discuss briefly the part played by the two last-named particles in atomic structure.

Compare the velocities attained by a proton and an α-particle each of which has been accelerated from rest through the same potential difference. L W65 II–12

5. During 15 days a mass of sodium-24 which was originally equal to 1 gramme disintegrates at the average rate of $8{\cdot}3 \times 10^{20}$ atoms per day. Taking the half-life of sodium-24 to be 15 days, calculate the number of atoms in 4 grammes of sodium-24.

6. Outline the main facts of radioactivity and briefly describe the properties of the radioactive radiations.

Radon is a monatomic gas of atomic mass 222 and with a radioactive constant equal to $2{\cdot}1 \times 10^{-6}$ sec^{-1}. Calculate the number of alpha particles emitted per second by 1 g of radon when free from disintegration products. Avogadro's number $= 6{\cdot}0 \times 10^{23}$ atoms per gram-atom. S 60 II–14

7. What is meant by the *half-value period* (*half-life*) of a radioactive material?

Describe how the nature of alpha particles has been established experimentally.

The half-life period of the body polonium-210 is about 140 days. During this period the average number of alpha emissions per day from a mass of polonium initially equal to 1 microgramme is about 12×10^{12}. Assuming that one emission takes place per atom and that the approximate density of polonium is 10 g cm^{-3} estimate the number of atoms in 1 cm^3 of polonium. N 62 II–12

8. Discuss the reaction represented by ${}^{1}{}_{7}^{4}\mathrm{N} + {}_{2}^{4}\mathrm{He} = {}^{1}{}_{8}^{7}\mathrm{O} + {}_{1}^{1}\mathrm{H}$, explaining the meaning of the subscript and superscript numbers. LW 63 II–12 (part)

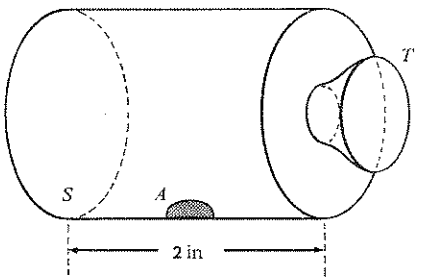
9. A hospital orders 10μc of cobalt-60 (half-life 5·3 years) What is the mass in grammes? (Decay constant $= 0{\cdot}693/T_{\frac{1}{2}}$; 1 curie $= 3{\cdot}7 \times 10^{10}$ disintegrations per second; Avogadro's number $= 6{\cdot}0 \times 10^{23}$ atoms per gram-atom.)

Chapter Six

Detectors of Radiation

1 Fluorescence

Since we cannot see alpha or beta particles or gamma rays, indirect means must be devised in order to detect them. One of the earliest methods was to observe the flashes of light as the rays hit a fluorescent screen, and in 1903 Crookes designed a simple instrument called a spinthariscope, which is still used to demonstrate the existence of radiations and the random nature of their emission. A modern version is shown in Fig. 44. It consists of a small radioactive source A and a fluorescent screen S, together with an eye-piece T for viewing the flashes. The same principle has recently been developed into one of the most sensitive means of detection by having the fluorescent material in the form of a liquid and crushing the radioactive sample into a powder so that it can be intimately mixed with the fluorescent material. The flashes of light energy produced by the fluorescence are converted into electrical currents by the process of photoelectric emission (see p. 192) and are then used to move a pen and so record the scintillations automatically. An instrument using this technique is called a *scintillation counter*.



A, alpha particle source; S, fluorescent screen; T, eye-piece.

Fig. 44 Spinthariscope. Demonstrates the continuous and random emissions from a radioisotope

2 Photographic plates

Radiations leave tracks if they travel through the emulsion of special photographic plates. An example is shown in Plate 5, which was obtained by soaking a sensitive plate for about two days in a solution of a salt of radium-224, at the end of which time four alpha particles had been emitted.

Another type of photographic record is known as an autoradiograph; an example is given in Plate 7, which shows up the parts of a leaf that have absorbed radioactive carbon-14 which emits beta particles. Plate 6 is an autoradiograph which was made by fixing a piece of gas mantle, which contains compounds of thorium from which gamma rays are emitted, to a dentist's X-ray plate and leaving it in position for about a week. The fibres of the gas mantle show up on the plate and the shadow was obtained by inserting a metal key between the thorium and the plate during the exposure.†

IONISATION

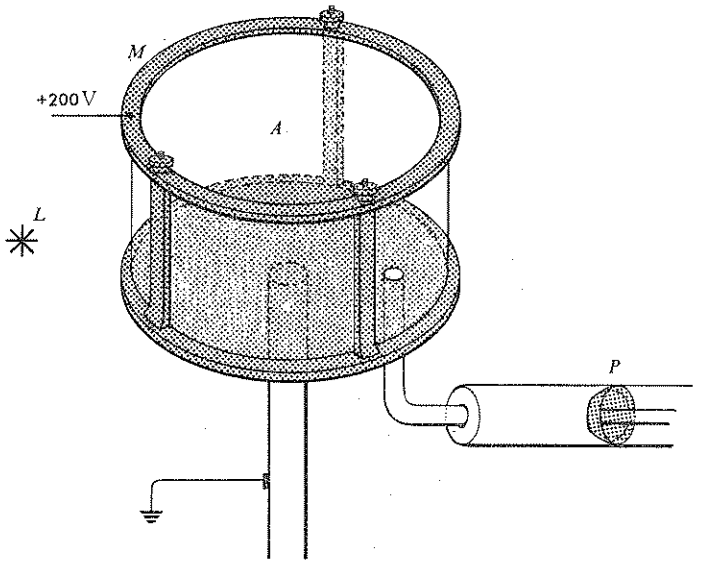
Most other types of detectors depend upon the ionisation produced by rays during their passage through matter. In a cloud chamber the positions of the ions are made visible by the condensation of liquid on them, while in other forms a potential difference applied across the detector will separate out the positive and negative ions and cause a current to flow.

3 Cloud chamber: expansion type

A supersaturated vapour will readily condense on ions. Since an alpha or a beta particle makes a track of ions as it passes through a gas, the entry of such a particle into a supersaturated vapour will be seen as a track of condensation looking like a miniature vapour trail of a high flying aircraft (Plates 3 and 4). In the expansion cloud chamber shown in Fig. 45, a little volatile liquid such as alcohol mixed with water is dropped in, and supersaturation is obtained by cooling the air in the chamber by means of adiabatic expansion, using a pump P which can reduce the pressure rapidly. The resulting fall in temperature produces supersaturation for a short period of time, during which the chamber is sensitive to ionising particles, but after about $\frac{1}{10}$th of a second it will have heated up again and no longer be sensitive. Hence, although particles may be passing through the chamber all the time, only those that pass immediately after the expansion will be detected. The cloud tracks soon become diffuse as the ions spread out by virtue of their thermal motion, and in order to clear the chamber of ions, so that it is ready for the next expansion, a potential difference of a few hundred volts is applied between the top and bottom. The chamber is illuminated from the side and viewed from above when the tracks may be seen or photographed.

The source is usually placed inside the chamber in order to prevent the

† ATOMIC ENERGY, I. D. Jaworski and A. Joseph, Macmillan.



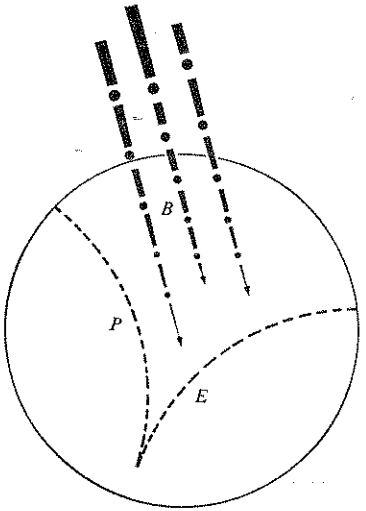
A, chamber containing super-saturated alchohol vapour; L, light source; M, metal ring for applying voltage; P, vacuum pump.

Fig. 45 Cloud chamber—expansion type. Sensitive immediately after pump is operated

absorption of particles by the walls, but a cloud chamber can also be used for detecting other types of charged particles such as those produced by cosmic rays which enter our atmosphere from outer space.

Alpha and beta particles can easily be distinguished because an alpha particle leaves a dense straight track whereas a beta particle leaves a track that is thinner and more tortuous as is seen in Plate 3. The track of an alpha particle is usually fairly short because of its limited range in air and Plate 4 shows tracks of alpha particles having two distinct energies emanating from a single source.

A cloud chamber is not suitable for gamma rays and X-rays because their ionising effect is too small. Charged particles such as protons can often be identified by applying a magnetic field vertically down the chamber, thereby making the track become curved in a direction dependant upon the sign of the charge with the curvature depending upon the energy and specific charge. The tracks shown in Fig. 46 are of two similar particles but with opposite charges—they are the tracks of an electron and a positron moving with equal velocities.



B, magnetic field into plane of paper; E, track of electron; P, track of positron.

Fig. 46 Electron-positron pair formed in a cloud chamber make tracks which have equal and opposite curvatures because their specific charges and energies are equal

4 Cloud chamber: diffusion type

The diffusion cloud chamber differs from the expansion type in being continuously operating, but only a thin layer inside the chamber is sensitive. Permanent supersaturation is obtained by having a pad at the top soaked in a volatile liquid such as methylated spirits or isopropyl alcohol while the bottom is kept cold by means of solid carbon dioxide, in this way there is an appreciable temperature gradient down the chamber. The alcohol condenses near the bottom but there will be an intermediate layer which remains supersaturated, so that any ionising particle going through this layer will leave a track. In order to clear the ions from the chamber a static charge is usually adequate and this may be obtained by rubbing the top with a suitable cloth.

The diffusion cloud chamber provides a convincing demonstration of the random nature of radioactivity, for if a small source is placed in the sensitive layer, tracks will be seen to spurt out in all directions from the source at irregular intervals. The energy with which the ionising particles are shot out from the source indicates that there must be a considerable amount of energy locked up inside a nucleus and this is the source of energy in nuclear power stations, as we shall see in Chapter 9. A diffusion cloud chamber

can also be used to show the rapid decay rate of the gas radon-220 which emits alpha particles; the short half-life of 54·5 seconds is clearly demonstrated by the rate at which the activity dies down after the gas has been squirted into the chamber, and a very rough estimate of its half-life can be made by measuring how long it takes for the rate of production of the tracks to be halved.

5 Detection by gold leaf electroscope

Alpha particles ionise the air sufficiently strongly for it to become slightly conducting, even at normal pressure. If a gold leaf electroscope is charged in the usual way and an alpha emitter is brought near to the cap then the charge will gradually be conducted away through the ionised air so that the leaves of the electroscope will collapse. This arrangement, however, is too insensitive to be of much practical value.

6 Spark gap for measuring the range of alpha particles

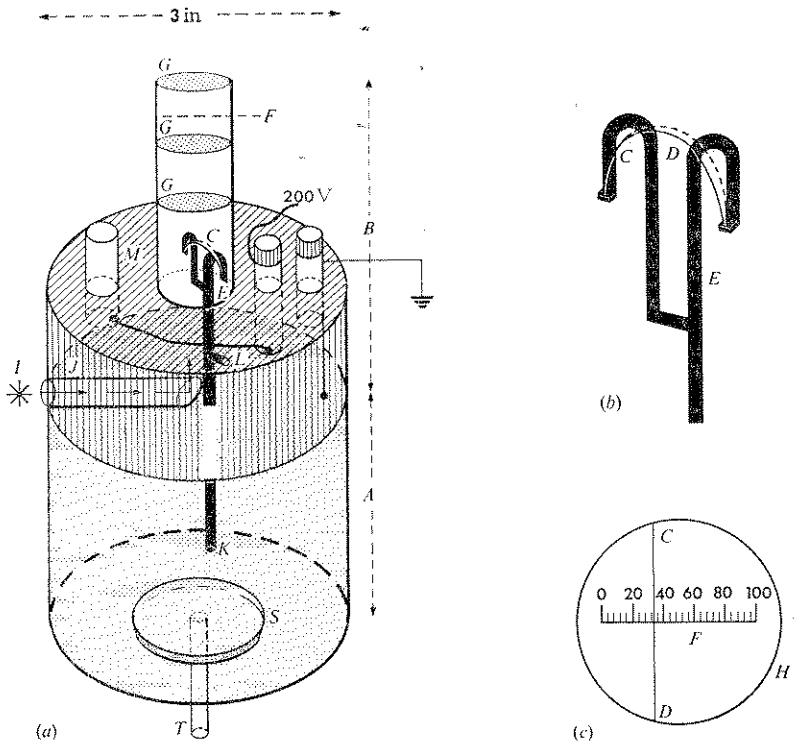
Another simple device for detecting alpha particles is a spark gap. It consists of two conductors separated by a few millimetres and given a potential difference of about 6 kV which is only just too low for a spark to pass. A single alpha particle moving near the gap will then ionise the air strongly enough to initiate a spark. A spark gap is sufficiently sensitive to measure the approximate range of alpha particles in air by finding the maximum distance between source and gap for sparks to be produced. It is not, however, sensitive enough to detect beta and gamma radiation.

IONISATION CHAMBER

7 Operation of ionisation chamber

An ionisation chamber is used, in conjunction with a device for measuring very small currents, to compare the activities of sources emitting alpha particles, and it can also be used for strong sources of beta particles. A simple form is shown in Fig. 47. It consists of a conducting chamber A, normally about three inches in diameter, with a platform D inside on which a source can be placed. The walls of the chamber are insulated from the platform and are usually maintained at a positive potential relative to the platform so that any pairs of ions formed in the chamber are separated out.

When an alpha particle emitted by the source passes through the air inside the chamber, it produces several hundred thousand pairs of positive ions and electrons; the electrons are attracted to the positively charged walls of the chamber and cause a current to flow in an external circuit connected between walls and platform. The magnitude of the current will



A, ionisation chamber; B, quartz fibre electroscope; CD, gold-plated quartz fibre (in (*b*)); E, aluminium support; F, scale; G, lenses forming microscope; H, field of view (in (*c*)), showing section CD of fibre and scale; I, light source; J, glass to reflect light past fibre; K, probe connecting fibre to ionisation chamber; L, spring and contact for charging; M, charging button; S, tray for radioactive source; T, inlet for radon gas.

Fig. 51 (a) *Ionisation chamber dosimeter*
(b) *Fibre and support*
(c) *Field of view*

The 'leaf' of the electroscope C is a very fine quartz fibre of diameter 0·004 millimetres and coated with gold so that it combines the good elastic properties of quartz with high conductivity (Fig. 51*b*). It is viewed through lenses G which magnify it by a factor of 45, and is supported on an aluminium frame E which is not visible in the field of view; only the central section CD of the fibre can be seen. A scale F in the eyepiece enables the position of the fibre to be read (Fig. 51*c*). The fibre and scale are illumi-

nated from outside the chamber by means of a 'light guide' J, which consists of a solid glass rod mounted horizontally with one end cut at an angle of 45° as shown, so that the light enters the outer end of the rod and is totally internally reflected up to the fibre and the scale.

The conducting support and fibre are connected to a probe K which extends into the ionisation chamber. The probe, support, and fibre are charged positively by means of a spring L which makes contact with a small projection on the probe when the charging button M is depressed and thereby connects it to a supply of about 200 volts. This causes the fibre to be repelled from the support so that the visible section CD is deflected to the left in the diagrams, and the charging voltage is adjusted until the fibre is at the end of the scale. When a source of alpha particles is placed inside the chamber the air will become ionised, and the electrons thus freed will be attracted to the positively charged probe which will thereby lose its charge. The activity of the source can therefore be measured by the rate of discharge of the probe and fibre and so can be found from the rate at which the fibre crosses the scale. The figures on the scale are arbitrary but it is usual for the reading to be zero when fully charged and a maximum when the voltage has dropped to about 100 volts. (For experimental details see p. 133.)

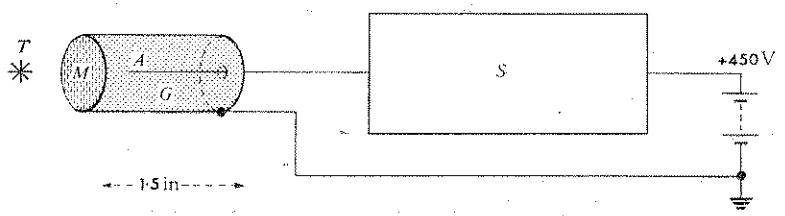
A similar instrument, called a pocket dosimeter, about the size of a pen torch, is used by personnel in industry and in hospitals. It incorporates a very small ionisation chamber, about 0·75 centimetre in diameter and is hermetically sealed. The walls of the chamber absorb alpha and beta particles though gamma and X-rays can enter, but in the absence of all radiation the rate of discharge is so slow that the charge is retained for several weeks. The dosimeter is carried in the pocket and the deflection is read after, say, two weeks when the position of the fibre will indicate the total dose of gamma or X-rays to which the operator has been exposed. The dosimeter can then be recharged and used again.

GEIGER MÜLLER TUBE

12 Construction of a G.M. tube

A Geiger Müller tube (usually shortened to G.M. tube) can be used to measure accurately the intensities of alpha, beta, gamma, and X-rays, and is sufficiently sensitive to detect individual alpha and beta particles. It is widely used in industry and medicine to locate radioisotopes whose presence can be detected in minute quantities, and in the laboratory for comparing the activity of specimens.

A typical modern tube is shown in Plate 9 and in Fig. 52. It consists of



A, anode; C, cylindrical metal cathode; G, gas at fairly low pressure; M, thin mica window; S, scalar or ratemeter; T, radiation source.

Fig. 52 Geiger-Müller counter. Scalar or ratemeter records output pulses from G.M. tube

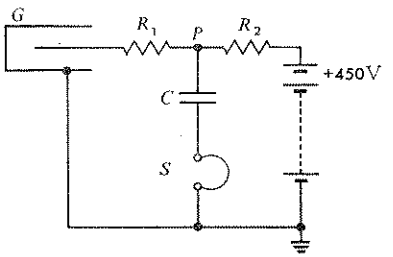
a thin wire about an inch long surrounded by a metal cylinder which contains a monatomic gas such as neon at a pressure of about 30 centimetres of mercury, together with a small trace of a halogen such as chlorine. The radiations enter through a mica window at the end of the tube, which must be very thin if the detector is to be used for alpha particles as otherwise they would be absorbed. The tube is connected into a circuit with the central wire as the anode, and a potential difference of about 450 volts is applied between the anode and the cylinder.

When a beta or other ionising particle enters, some neon atoms are ionised, forming positive ions and free electrons; these electrons are collected very rapidly at the anode, thereby giving a pulse of current which may be used to make an audible click or be recorded in some other way. The processes which take place inside the tube (described in section **14**) result in the original number of free electrons being amplified enormously so that a reasonably large current pulse is produced by the entry of a single particle. The chlorine *quenches* the discharge, making the duration of the pulse so short that the tube is ready to receive the next particle within about $\frac{1}{10\,000}$th of a second.

The output current pulses may be indicated in two fundamentally different ways: a scalar records the arrival of each individual pulse separately whereas a ratemeter records the number of pulses in a given time, i.e. the rate at which they arrive. The combination of G.M. tube and indicator will be referred to as a *G.M. counter*.

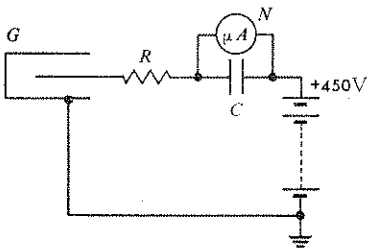
13 Scalar and ratemeter

A scalar clocks up the arrival of each individual pulse by means of electrical circuits which are usually complex, but a simple form which gives audible clicks is shown in Fig. 53. The small pulse of current, produced when the electrons collected by the anode flow to the d.c. supply, sets up a potential difference across a high resistance R_2 so that the potential at P falls momentarily. This partially discharges the condenser C making a current pass through the earphones S and thereby produces an audible click. The function of the resistance R_1 is to protect the tube, which is sometimes damaged if it is connected directly to a condenser. This simple circuit can only be used for very low count rates of one or two per second which can be distinguished as separate clicks.



C, condenser 330 μμF; G, G.M. tube; R_1, R_2, resistances 2·7 MΩ; S, earphone.

Fig. 53 Simple scalar circuit—giving audible clicks from G.M. tube pulses



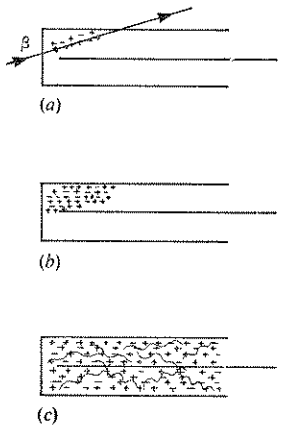
C, condenser 1 000 μF; G, G.M. tube; N, microammeter having high resistance (1 kΩ); R, resistance 3·3 MΩ.

Fig. 54 Principle of ratemeter circuit—microammeter indicates mean rate of pulses

The principle of a ratemeter circuit is shown in Fig. 54. The current pulses charge up a condenser C, which then discharges gradually through a high resistance microammeter N, so that the pulses are smoothed out and an average current is recorded. This current will be proportional to the rate of arrival of the pulses so long as the magnitude of each pulse is the same, and this condition is found to hold provided that the potential difference supplied across the G.M. tube is constant. A high resistance R is included to protect the G.M. tube. (See Appendix **8** for details of circuit.)

*14 Operation of G.M. tube

When an ionising particle enters a G.M. tube it will create pairs of ions in its track consisting of positive neon ions and electrons (Fig. 55*a*). Because of the shape of the electrodes, the field is radial and is very strong near the anode (Fig. 56). Any free electron in this region will be accelerated rapidly and will soon acquire enough energy to ionise other atoms by collison, thereby freeing further electrons and the process is cumulative (Fig. 55*b*). This rapid increase in the number of electrons is known as an *avalanche*.



(a) *Beta particle enters, forming ions in its path*
(b) *Avalanche of electrons, resulting from ionisation by collision*
(c) *Further ions produced by photons, making ionisation spread throughout tube*

Fig. 55 Production of ions in G.M. tube

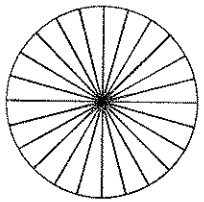


Fig. 56 Radial electric-field—very strong near centre

The amplification of the number of ions in a G.M. tube is further increased by a special feature which distinguishes a G.M. tube from other forms of ionisation chamber. When some of the free electrons collide with neon atoms, instead of ionising them they pass on some energy to the atom which then becomes *excited*, and the atom loses the extra energy by emitting a photon of ultraviolet or visible light; if the photon is absorbed by another excited atom the latter can be ionised, thereby releasing more

electrons, and these produce further avalanches. Since photons are unaffected by electric fields they can go in any direction so that the discharge spreads rapidly throughout the tube (Fig. 55*c*). In this way an amplification as high as 10^8 can be reached, the total number of ions depending upon the geometry of the tube and the potential difference applied but not upon the number of ions produced by the original particle which entered.

The function of the chlorine is to absorb energy without emitting photons or being ionised. Surplus energy in a polyatomic molecule is likely to be used in dissociating the atoms, and excess energy is converted into kinetic energy of the fragments. Thus the chlorine tends to absorb photons and convert excess energy into kinetic energy, and hence into heat, and in due course the atoms recombine so that no permanent change takes place. Thus, the monatomic gas neon is selected because of its proficiency in producing amplification through the agency of photons, whereas a halogen, chlorine, is selected for the reverse reason, namely its tendency to absorb photons, thereby preventing the discharge from continuing after the first burst, i.e. it acts as a quenching agent. The quantity of chlorine incorporated must be carefully controlled in order to quench the later discharge but not to stop the initial burst, and in practice this quantity is found to be about 1 part in 1 000 of the total gas present.

Because the total number of ions produced does not depend upon the number generated by the incoming particle, a G.M. tube does not distinguish between the arrival of an alpha and a beta particle. However, the type of radiation can be determined by using absorbers outside the tube and by noting the thickness which is required to cut off the radiation. When receiving gamma or X-rays, the operation of the tube is dependent upon electrons released from the walls, or upon the small ionising effect in the gas itself due to the passage of the rays, so a lot of radiation can pass through the tube without releasing the electrons necessary to initiate a pulse, and therefore the G.M. tube only detects about 1 per cent of the photons which enter. In spite of this, the tube is still sensitive and the pulse rate can be used for comparing the intensities of gamma rays or of X-rays and for detecting their presence even in very small quantities.

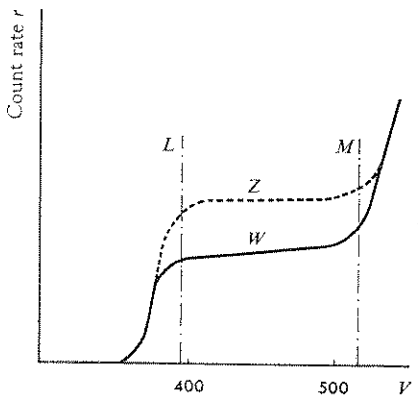
*15 Organically quenched G.M. tube

Some G.M. tubes use quenching devices other than halogens. One type of tube is quenched by organic compounds which undergo chemical changes which are not reversible when they absorb energy from photons, so that the life of such tubes is limited. An organically quenched tube has the further disadvantage of requiring a much higher operating voltage (1–2 kV) so that this type of tube is now largely replaced by halogen quenched ones.

16 Output: voltage curve for a G.M. tube

In order to investigate how the output from a G.M. tube varies with the voltage applied, the circuit is set up as shown in Fig. 52, page 116, except that a variable voltage supply is used, whose magnitude may be measured with the aid of a voltmeter connected directly across it. A beta particle emitter such as 0·1 μc of strontium-90, which has a long half-life (28 years), is used. The emitter is placed at a fixed distance from the tube so that the radiations are received at a constant rate for the duration of the experiment, except for the unavoidable random fluctuations; in order to obtain reliable results the source should be placed so that the count rate is fairly high, as will be explained on p. 124.

If the counts per minute, *r*, are found using a scalar for various measured voltages and the results plotted, a curve is obtained as shown in Fig. 57 which falls into three distinct parts. For very small voltages the current is extremely small because the electrons are not accelerated sufficiently to produce further ionisation by collisions. Over the next range of voltages, the output is almost steady and is produced by the mechanism described above. The curve then rises steeply because the current is no longer quenched by the chlorine and a continuous discharge takes place similar to that in a low pressure discharge tube. The voltage range LM over which the output is fairly steady is known as the *plateau* of the tube, and when in use the potential difference applied across the tube is selected to be within this range. For a stronger source, the corresponding curve is shown dotted and



LM, plateau; r, counts per minute; *V*, potential difference across tube; W, weak source; Z, strong source.

Fig. 57 G.M. tube. Output: voltage. The tube is operated at a voltage within the plateau range LM

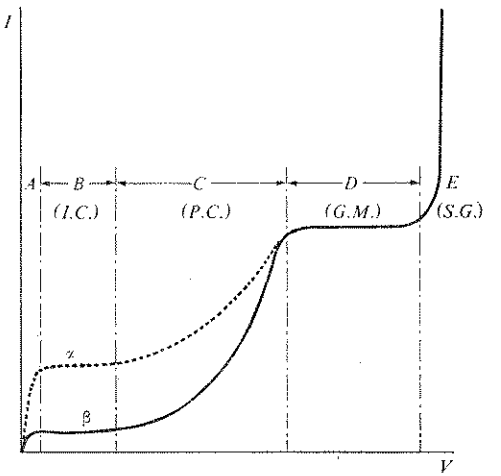
indicates that the number of pulses per minute has increased but that the plateau voltages have remained the same.

If a ratemeter is used instead of a scalar, the output over the plateau range will rise slightly more because there is a small increase in size of pulse as the voltage increases, but there will be sharp changes in gradient at the ends of the plateau signifying a change in the pulse rate.

When using a G.M. tube the supply voltage should be well within the plateau range so that voltage fluctuations will have a minimal effect on the output.

*17 Relation between detectors

A graph of current plotted against the potential difference applied between parallel plates in a gas at normal pressure is shown in Fig. 58. It will be seen that the detectors described above employ different sections of this curve—in practice the voltage needed to operate a G.M. tube is made considerably smaller than is indicated in this graph by using a radial field and reduced pressure, but the diagram may serve to show where it



A, ions recombine; B, all ions collected, **ionisation chamber;** C, further ionisation by collision, **proportional counter;** D, further ionisation by photons, **G.M. tube;** E, continuous discharge, **spark gap;** I.C., ionisation chamber; P.C. proportional counter; G.M., G.M. tube; S.G., spark gap.

Fig. 58 Relation between detectors. Ionisation current: potential difference applied between parallel plates at normal pressure, showing sections of graph utilised by various detectors. Alpha and beta particles give different currents until section D is reached. (In practice, a G.M. tube is at low pressure and so needs a smaller potential difference than is indicated here)

stands in relation to other detectors. It will also be noticed that different ionisation currents are developed for alpha and beta particles until the G.M. region is reached, so that some detectors can be used to distinguish directly between these particles. The response of a G.M. counter is the same for the different particles, but the particles can readily be distinguished by finding what type of absorber placed in their path will prevent them from reaching the tube. (Section C of the graph is utilised in a *proportional counter*, details of which are outside the scope of this book.)

Detector	Radiations	Notes	Supply voltage
Expansion cloud chamber	α, β	detects and identifies individual charged particles intermittent operation	300 volts for removing ions
Diffusion cloud chamber	α, β	as above continuous operation	300 volts for removing ions
Fluorescence	α, β, γ, X	can be made extremely sensitive	—
Photography	α, β, γ, X	useful for detecting small traces of radioisotopes	—
Gold leaf electroscope	α	demonstrates ionisation very insensitive and of little practical use	charged electrostatically
Spark gap	α	approximate range of α particles	6kV
Ionisation chamber and pulse electroscope	α (β)	compares activities measures half-life absorption experiments	2kV
Ionisation chamber dosimeter	α (β)	as above	200 volts
G.M. counter	α, β, γ, X	very sensitive to individual particles extensively used	450 volts
Proportional counter	α, β, γ, X	sensitive, can differentiate between radiations	800 volts

Problems on Chapter Six

1. Give an account of the chief properties of $\alpha-$, $\beta-$ and $\gamma-$ radiations.

Describe how you would measure the range in air of $\alpha-$particles from a given source. O 64 II–15

2. What is a *radioactive isotope*? Explain what information is conveyed by the following equations referring to the production and decay of radioactive sodium:

$$^{23}_{11}\mathrm{Na} + ^{1}_{0}n \rightarrow ^{24}_{11}\mathrm{Na}$$
$$^{24}_{11}\mathrm{Na} \rightarrow ^{24}_{12}\mathrm{Mg} + ^{0}_{-1}e$$

Discuss briefly some ways in which the radiations from radioactive nuclei may be detected. L 65A II–12

3. Describe detectors suitable for each of the following:
(*a*) comparing the activities of two similar sources emitting alpha particles (*b*) finding a small source which emits gamma rays and which has been lost in the laboratory, and (*c*) determining whether the emissions from a given source are alpha particles or beta particles.

4. Give a brief account of the nature and properties of radiations from naturally occurring radioactive substances.

A deposit of radium C (*i.e*, *bismuth*-214) is placed on a horizontal thin straight wire A above which a fine slit B is placed parallel to the thin wire and 6 cm above it. Alpha particles from A pass through B and are detected at P on a photographic plate placed in a horizontal plane 6 centimetres vertically above B. The whole apparatus is enclosed in a highly evacuated chamber. A uniform magnetic field, of induction 10 000 gauss is now applied to the region between A and B in a direction parallel to the wire, while the space between B and P remains field free. Under these conditions the alpha particles are detected on the plate 4·5 millimetre from P. Estimate the velocity with which the alpha particles are emitted from the radium C, given that e/m for alpha particles is $4{\cdot}80 \times 10^3$ e.m.u. g^{-1}. (Relativistic effects may be neglected; 1 weber $\mathrm{metre}^{-1} = 10^4$gauss; 1 coulomb $= 10^{-1}$ e.m.u. of charge.) L Sp. 63–12

the thickness of an absorber, which is grammes per square centimetre. The maximum range in a material also depends upon the energy of the incident beta particles.

6 Absorption of gamma rays by lead

A suitable source of gamma rays is 5 μc of cobalt-60 (half-life 5 years), and the apparatus is set up as in the previous experiment except that lead screens replace aluminium ones because of the greater penetrating power of gamma rays. Counts must be corrected for background radiation as before, but absorption by the end window of the G.M. tube and by the air is negligible.

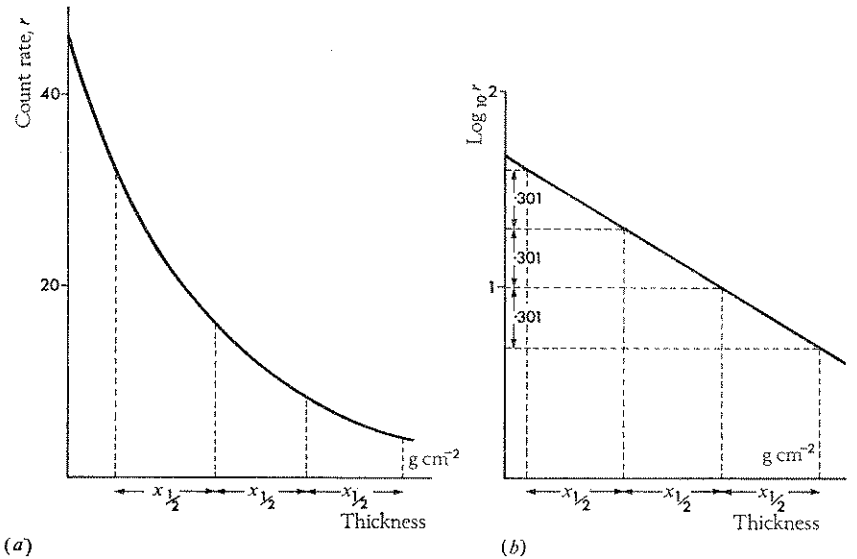


Fig. 61 Absorption of gamma rays by lead. Count rate is never reduced to zero

The intensity of the gamma rays penetrating the lead and reaching the counter is found to fall off as shown in Fig. 61*a* and never reaches zero ($I=I_0e^{-\mu x}$, where x is thickness) so that gamma rays are never entirely absorbed. There is therefore no maximum range and the absorption of the material is measured in terms of half-thickness, which is the thickness that halves the intensity of the rays; its value may be determined directly from the graph of count rate : thickness as shown in Fig. 61*a*, where each ordinate marked is exactly half of the preceding one.

A more convenient graph is obtained by plotting $\log_{10}$ (count rate) : thickness†, as this is found to be linear (Fig. 61*b*). The half-thickness can then be evaluated as follows:

By definition, the count rate r is reduced to $\frac{1}{2}r$ when the absorber is increased by its half-thickness,

but $\log_{10}\frac{1}{2}r = \log_{10} r - \log_{10} 2 = \log_{10} r - 0{\cdot}301$

$\therefore \quad \log_{10} r - \log_{10} \frac{1}{2}r = 0{\cdot}301$

But this corresponds to an increase in the absorber equal to its half-thickness. Hence when the absorber is increased by the half-thickness then $\log_{10}r$ is reduced by 0·301.

Thus the gradient of the graph is equal to $\dfrac{-\ 0{\cdot}301}{\text{half-thickness}}$

7 Inverse square law for gamma rays in air

Air acts as a transparent medium to gamma rays, i.e. the loss in energy of a parallel beam due to absorption by air is negligible. However, the intensity *per unit area* of rays emanating from a point source decreases with distance because the total energy is spread out over a greater area as the distance increases (see p. 93). Since other electromagnetic waves, such as light, obey the inverse square law, it is reasonable to suppose that the intensity per unit area of gamma rays also decreases inversely as the square of the distance from the source.

In order to investigate this law, a source of 5 μc of cobalt-60 is fixed at different known distances d from a G.M. counter and the corresponding count rates are found. Because of uncertainties in the zero of distance, due to the finite size of the detector and the slight absorption by the window, the true value for the distance is $(d + a)$, where a is unknown but may be assumed to be constant. Taking r as the count rate, then if the inverse square law is applicable, a graph of $r : \dfrac{1}{(d+a)^2}$ will be a straight line through the origin; but because a is unknown it is better to plot $\dfrac{1}{\sqrt{r}} : d$ which gives a linear graph having an intercept $d = -a$ if the inverse square law applies.

A similar experiment carried out with beta or alpha particles in air would not give a linear graph because, in addition to the decrease in intensity per unit area due to the rays spreading out (as for gamma rays), there is also a considerable loss in *total* intensity due to absorption by the air.

† $I=I_0e^{-\mu x}$. $\therefore \log_{10} I=\log_{10} I_0-\mu x.\log_{10} e$. Hence $\log_{10} I : x$ is a linear graph of gradient $-\mu.\log_{10} e=-0{\cdot}434\mu$.

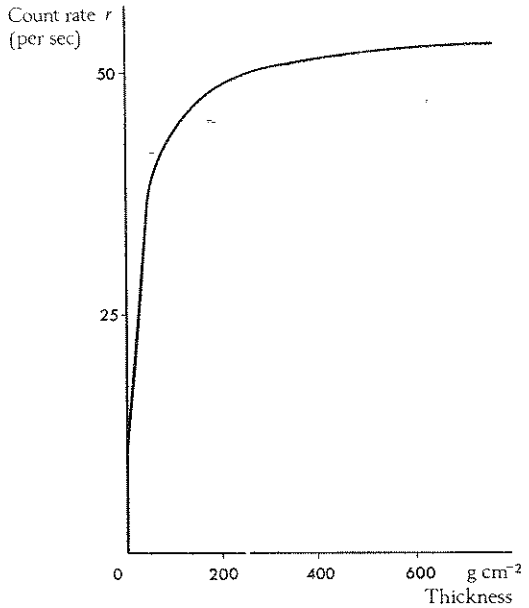


Fig. 64 Back scattering of beta particles depending on thickness of aluminium scattering foil

paint on a base consisting of elements having atomic weights lower than that of lead.

10 Half-life of source using G.M. counter

A suitable source for this experiment is the alpha-particle emitter radon-220, since it is easily obtained from natural thorium (p. 135), has a short half-life of less than a minute, and the activity of the daughter products is small enough to be negligible. However, radon is a gas, and it must be contained in a special 'cell' which has a window so thin that it allows the alpha particles to emerge with enough energy to pass through the window of the G.M. tube.

The cell is set up as close as possible to a G.M. counter and radon is forced into it using the source bottle described below on p. 135. Count rates over a short period of about 10 seconds are taken at approximately half-minute intervals for three or four minutes, and readings are corrected for background radiation. The time T at which each of the counts is begun is also noted and the corresponding activity is taken to be that at the middle of the counting period, i.e. at a time $T + \frac{1}{2}p$.

A decay curve showing how activity varies with time may be obtained by plotting count rate r against time $T + \frac{1}{2}p$ and will take the form shown in Fig. 41. (p. 98). From the laws of radioactive decay, the activity $\frac{dn}{dt} = -\lambda n$, where λ is the decay constant, and hence when the number of unchanged atoms n is halved then the activity is also halved. The half-life can therefore be found directly from the graph by estimating the time that elapses for the count rate to drop to half its value.

A less direct method of deducing the results, but one for which the graph is linear, is to plot $\log_{10} r$ against time; during the half-life the count rate is reduced from r to $\frac{r}{2}$, but

$$\log_{10} \frac{r}{2} = \log_{10} r - \log_{10} 2 = \log_{10} r - 0{\cdot}301$$

Therefore $\log_{10} r - \log_{10} \frac{r}{2} = 0{\cdot}301$.

Thus the half-life is the time required for $\log_{10} r$ to be reduced by 0·301, and hence the gradient of the graph is equal to $\frac{-0{\cdot}301}{\text{half-life}}$.

(Compare this with the evaluation of the half-thickness of an absorber using a linear graph—section **6**, p. 129.)

This experiment is not easy to perform because alpha particles are largely absorbed by the windows of the gas cell and the G.M. tube, so that the count rates are low and this makes the random fluctuations vitiate some of the readings.

An alternative source is the beta particle emitter bismuth-212 whose half-life is 60 minutes. This can be obtained from thorium, as described on p. 135, but it is then mixed with lead-212 which is also a beta particle emitter with a comparable half-life (10 hours) so that for good results these two isotopes must be separated chemically (see Appendix **8**). The half-life is measured as described above but as its value is considerably longer than that of radon-220, the count rates can be taken over a longer period of time, say half a minute, and repeated at two-minute intervals.

***11 Half-life of a source using an ionisation chamber dosimeter**

An alternative method of measuring the half-life of a weak radon source emitting alpha particles is to use an ionisation chamber dosimeter (p. 113) and thus obviate the absorption effects of the windows of a G.M. counter and of a gas cell.

The dosimeter is connected to a supply whose voltage is adjusted until the fibre is at the end of the scale when the charging button is depressed.

Radon-220 from a source bottle is then forced into the chamber, the dosimeter is charged, and the activity of the radon is determined by measuring the period p for the fibre to cross a section s of the scale, using a stop-watch —the activity is proportional to the rate of discharge, $\frac{s}{p}$, which measures the ionisation current. The time T at which the measurement is begun is also noted using a separate clock, and hence the mean time at which the measurement is taken is $T + \frac{1}{2}p$. The dosimeter is re-charged and measurements of T and p are repeated in rapid succession for three to four minutes. A correction is made, if necessary, for background radiation and for leakage of the dosimeter, by finding the period for the fibre to cross the same section of the scale when no other source is present; this correction must be *added* to the period measured because leakage will make the fibre move more quickly and hence decrease the period p. A typical set of readings is given below.

Time at start of measurement, T sec	Section of scale used, s	Period to cross scale, p sec	Activity (rate of discharge) s/p	Log (activity) $\log_{10} s/p$	Mean time, $T+\frac{1}{2}p$ sec
51	80	4·1	19·5	1·29	53
74	80	5·4	14·8	1·17	77
99	80	7·3	11·0	1·04	103
132	80	12·0	6·7	0·83	138
172	40	9·9	4·0	0·60	177
214	40	17·9	2·2	0·34	223
266	20	16·4	1·2	0·08	274

(The correction for background radiation and leakage was negligible)

The half-life may be deduced by plotting activity against time and estimating the time taken for the activity to be halved. Alternatively the half-life may be deduced from a linear graph, by plotting $\log_{10}$ (activity) against time and using the relation gradient $= -\frac{0{\cdot}301}{\text{half-life}}$ as explained in the preceding section.

12 Estimation of half-life of a source in a decay series

The half-life of an isotope for which the value is very large or very small may be determined from its relative abundance in a decay series which has reached equilibrium, provided that the half-life of one member is known. When in equilibrium the decay constants λ and the number of atoms of each isotope present are related by the equations $\lambda_1 n_1 = \lambda_2 n_2 = \lambda_3 n_3 = \ldots$ (p. 101). The decay constant λ is inversely proportional to the half-life

$T_{\frac{1}{2}}$ (p. 97), and the number of atoms $= \frac{\text{mass present}}{\text{atomic mass}} = \frac{w}{M}$

Hence $\frac{1}{(T_{\frac{1}{2}})_1} \cdot \frac{w_1}{M_1} = \frac{1}{(T_{\frac{1}{2}})_2} \cdot \frac{w_2}{M_2} = \frac{1}{(T_{\frac{1}{2}})_3} \cdot \frac{w_3}{M_3} = \ldots$

where w refers to the mass present and M to the atomic mass.

13 Sources with short half-lives

If the half-life of a material is short it cannot be stored in the usual way and special measures must be provided for producing it. One such isotope is radon-220 (sometimes called thoron), which is an inert gas and is formed in the decay of natural thorium.

$$^{228}_{90}\text{Th} \xrightarrow[1{\cdot}9 \text{ years}]{\alpha} {}^{224}_{88}\text{Ra} \xrightarrow[3{\cdot}6 \text{ days}]{\alpha} {}^{220}_{86}\text{Rn} \xrightarrow[54{\cdot}5 \text{ seconds}]{\alpha}$$

Thorium-228 is produced from natural thorium-232 as indicated on p. 99. The thorium in a compound such as thorium hydroxide will disintegrate, and if it is in a closed container an appreciable amount of the gas radon-220 will accumulate in the course of a few hours. The thorium hydroxide is usually kept in a small polythene bottle which is closed by a stopper carrying a rubber tube with a crocodile clip. When the gas is required, the clip is opened and the bottle is squeezed. Such a bottle can be used about six times in succession, but a period of several hours is then needed for the radon to accumulate again.

The source bottle containing radon may also be used to provide a solid source of beta particles, and the method by which this source is formed is instructive. As the nucleus of radon-220 disintegrates it emits an alpha particle with considerable velocity, and in order to conserve momentum the nucleus recoils. The recoil is sufficient to separate the nucleus from many of its orbital electrons so that for a brief interval of time it becomes a positively charged ion. If, therefore, an electrode is placed inside the bottle and is maintained at a negative potential of about -200 volts for a day or two, it will collect the products of the radon decay. By a consideration of the half-lives of the decay products it will be seen that the isotopes that are collected in appreciable quantities are lead-212 and bismuth-212. Both of these isotopes emit beta particles, having half-lives of 10 hours and one hour respectively, and they can be separated chemically if a pure source is required (see Appendix 8.)

Problems on Chapter Seven

1. Describe how the maximum range of beta particles in aluminium can be measured. How is the experiment modified for investigating the

absorption of gamma rays by a solid? Give reasons for these modifications.
2. How does the intensity of gamma rays depend upon the distance from the source in the absence of liquid or solid screens? Why does the same law not apply to alpha or beta particles when travelling through air?
3. The activity of radium-220 at one-minute intervals is proportional to 100, 47, 22, 10. By plotting a suitable graph, find its half-life.
4. Using the results given on p. 134 deduce the half-life of radon-220 by plotting (*a*) activity against time and (*b*) $\log_{10}$ (activity) against time.
5. State the differences in nature of alpha, beta, and gamma radiations from a radioactive source.

Describe the differences in their properties giving experimental evidence of any *two* of these differences. L 64 II–12
6. A given material is described as being *radioactive* with a *half-value period* (*half-life*) of two days. Explain the terms printed in italics.

Describe and explain experiments that could be performed to identify the types of radiation which radioactive substances can emit. N 65 II–14
7. Find the mass of uranium-238 in equilibrium with 1 gramme of radium-226, given that the half-lives are $4{\cdot}56 \times 10^9$ years and 1 600 years respectively.
8. Find the half-life of polonium-210 if that of radium-226 is 1 600 years, and 1 gramme of radium is in equilibrium with 0·22 mg of polonium.

Chapter Eight

Applications of Radioactivity

1 General

In addition to the naturally occurring radioisotopes such as radium, hundreds of others have been made artificially. These isotopes are now produced on a large scale with the aid of nuclear reactors, and their applications in medicine, industry, and pure research are numerous. The choice of isotope often depends upon considerations of its half-life because it must remain active long enough for the purposes for which it is required but not so long that it becomes a radiation hazard when once it has served its purpose.

The applications may be grouped under the following headings:

a Tracer technique—in which a very small quantity of a radioisotope is injected into the material to be studied and its position is subsequently located with precision.
b Inhibition of growth in living organisms.
c Increase of mutation rate.
d Photography.
e Dating of archaeological specimens by measuring the extent by which a radioisotope has decayed.
f Thickness gauges depending upon the property that materials absorb radiation.
g Luminous sources—using the fluorescent effect.
h Chemical analysis.

2 Tracer technique

In general terms the tracer technique consists of introducing a small quantity of radioactive material deliberately into the substance to be investigated and tracing its subsequent path by means of a G.M. counter or by photography. The method can be made extremely sensitive. The movement of the radioisotopes may be due to the movement in bulk of the material into which it has been injected or it may be due to the passage of the radioactive element as it goes from one compound to another during chemical changes. Some specific examples are given below.

3 Tracer technique to investigate movement

The flow of water in underground pipes can be investigated by injecting a gamma-ray emitter, because the penetrating power of gamma rays enables

per nucleon of carbon-12 is equal to +0·008 a.m.u. (from section 6) which equals 7·6 MeV.

Thus, we can conclude that a particle in a very stable nucleus has a *small* potential energy and small mass, but it has a *large* binding energy.

FISSION

8 Principles of nuclear fission

The great instability of the heavier elements, indicated by the large masses per nucleon, results in certain isotopes undergoing fission spontaneously, the nucleus breaking up into two smaller nuclei. This spontaneous fission follows laws of probability similar to those of radioactivity, and such isotopes have a definite half-life.

Fission can also be induced by bombarding certain nuclei with neutrons. One of the fuels suitable for releasing energy by fission induced in this way is plutonium-239 and another is an isotope of uranium, U-235, of which natural uranium contains about one part in 140; if such a nucleus is hit by a slow-moving neutron, the latter is absorbed, forming uranium-236

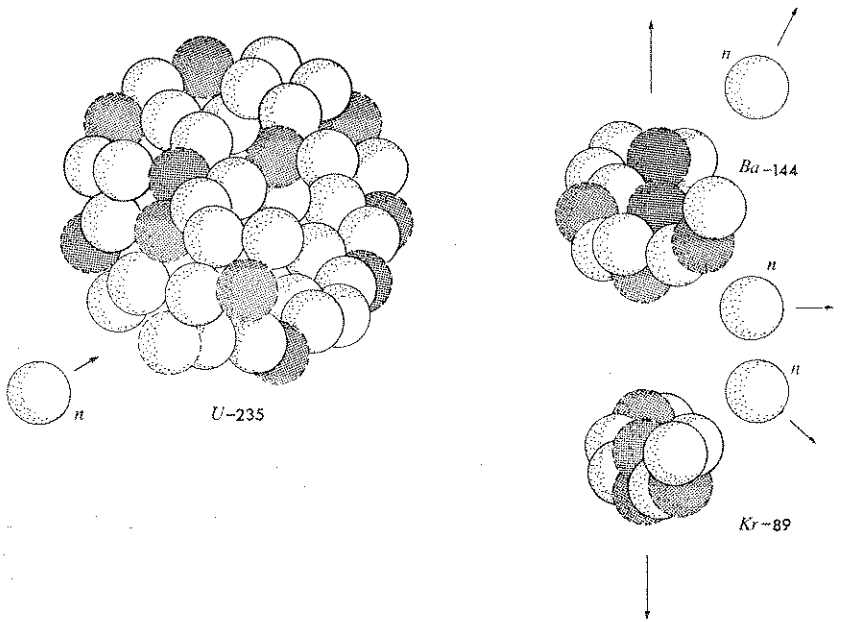


Fig. 68 Fission of uranium-235, producing barium-144 and krypton-89 and releasing three fast neutrons

which very soon undergoes spontaneous fission, and the net result therefore is that the uranium nucleus is split into two parts, as illustrated in Fig. 68. The pair of elements formed is largely a matter of chance so that there is a considerable diversity among the fission products and many of these are radioactive; this is the source of danger associated with fall-out from nuclear explosions. One pair of elements that can be produced is strontium-90 and xenon-143. Strontium-90 has a half-life of twenty-eight years, which is long compared with those of most other fission products, these half-lives are usually measured in terms of only a few days or even seconds. Strontium-90, therefore, remains a source of radiation over a long period and is particularly objectionable because it tends to enter the human reproductive organs where it can affect future generations.

Another pair of fission products is barium-144 and krypton-89 and these are accompanied by three fast-moving neutrons and the release of 190 MeV of energy. This may be expressed by the following equation:

$$^{235}_{92}\mathrm{U} + \underset{\text{(slow)}}{^{1}_{0}n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\underset{\text{(fast)}}{^{1}_{0}n} + 190\text{MeV}$$

The equation includes energy as one of the 'products' of the reaction, and its value may be obtained from considerations of the masses,† i.e.

$$\text{mass of } {}^{235}_{92}\mathrm{U} + {}^{1}_{0}n = 234{\cdot}99 + 1{\cdot}01 = 236{\cdot}00 \text{ a.m.u.}$$
$$\text{mass of } {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3{}^{1}_{0}n + \text{energy} = 143{\cdot}87 + 88{\cdot}90 + 3{\cdot}03 + E$$
$$= 235{\cdot}80 \text{ a.m.u.} + E$$

Since mass + energy is conserved,

$$\text{the energy } E \text{ released} = 236{\cdot}00 - 235{\cdot}80 \text{ a.m.u.}$$
$$= 0{\cdot}20 \text{ a.m.u.}$$
$$\text{which equals } 0{\cdot}20 \times 931 = 190 \text{ MeV.}$$

This energy is small, being about 3×10^{-4} erg but it is a formidable contribution from a single atom, and in a nuclear reactor or during a nuclear explosion very large numbers of atoms undergo fission and the total energy released can be enormous. The energy is mainly in the form of radiant energy such as radiant heat, light, and gamma rays, or in the form of heat resulting from the kinetic energy of fission products.

9 Chain reaction

If one or more of the neutrons ejected during fission can be used to promote further fissions then the reaction is self-sustained and is known as a

† In this calculation *nuclear* masses have been used. It is more usual to use *atomic* masses, which include the masses of orbital electrons, because they are more readily available from tables. But since the same number of electrons would be included on both sides of the equation, the value obtained for the energy would not be affected.

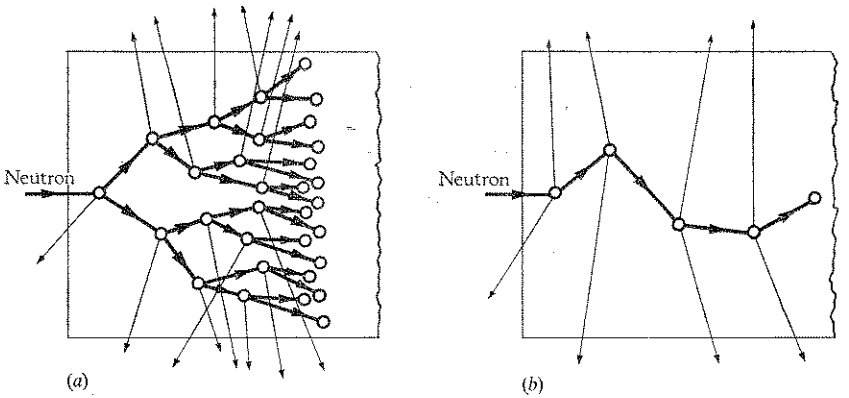


Fig. 69 (a) *Explosion. Each fission causes* two *further fissions so that reaction builds up rapidly*
Fig. 69 (b) *Controlled chain reaction. Each fission causes* one *further fission so that reaction proceeds steadily*

chain reaction. The energy from the fissions in a chain reaction can be released either in the form of an explosion or in a steady and controlled way. The explosive release is illustrated in Fig. 69*a* in which the fission of one nucleus ejects three neutrons, and of these an average of one neutron escapes while two neutrons produce further fissions; this results in a very large number of nuclei undergoing fission in a very short space of time, so that an explosion ensues. Fig. 69*b*, on the other hand, illustrates the controlled release of energy in which, on an average, each fission promotes only one further fission, so that a steady supply of energy is produced.

It will be seen that a critical balance is required for the production of controlled nuclear energy as too great a probability of neutrons promoting further fissions will result in an explosion, while too small a probability will stop the reactor from operating. In the case of uranium-235, the average number of neutrons released per fission, when all the possible fission products are considered, is about 2·5 so that a reactor 'goes critical' when the probability of a neutron promoting a further fission is 1 in 2·5.

As we have seen, the fissions occurring in a nuclear reaction are initiated by neutrons, and the type of reaction that takes place often depends upon the velocity of the neutron when it hits the nucleus. Reactions may roughly be classified according to the velocity of the neutrons into slow or fast, being typically about 2 miles per second and 600 miles per second respectively. The reaction discussed in the preceding section is classified as a slow reaction.

10 Fission bomb

In order to produce an explosive chain reaction there must be a high probability that a neutron produced during fission will collide with another nucleus of uranium-235. If the volume of the uranium fuel is very small it will have a relatively large surface area and this will facilitate the escape of neutrons and so reduce the probability of further fissions; there is therefore a critical size for the fuel, below which a chain reaction will not take place. In addition, the shape of the fuel is of importance and there must be a sufficient concentration of the fissionable nuclei in it for the neutrons to have a good chance of hitting one of them. The concentration of fissionable uranium-235 nuclei can be increased by using 'enriched' fuel in which the proportion of this isotope can be made greater than that occurring naturally (99·3 per cent of natural uranium is U-238). It will be seen that the critical size of a bomb depends upon a number of factors so that different types of bombs vary considerably in their dimensions; the diameter can be as small as one foot.

The two bombs dropped on Japan during World War II used different methods for concentrating the fuel sufficiently to produce an explosion. In the first bomb the fuel was uranium-235 and it was carried in two sections, each section being below the critical size, and the two sections were shot rapidly together when the explosion was required; this is illustrated in Fig. 70*a*. In the second bomb the fuel was plutonium-239 which was spread into a fairly large volume, i.e. it had a relatively low density; it was then compressed to form the high concentration required by the simultaneous detonation of conventional chemical explosives arranged round the outside as shown in Fig. 70*b*. In both cases the nuclear explosion

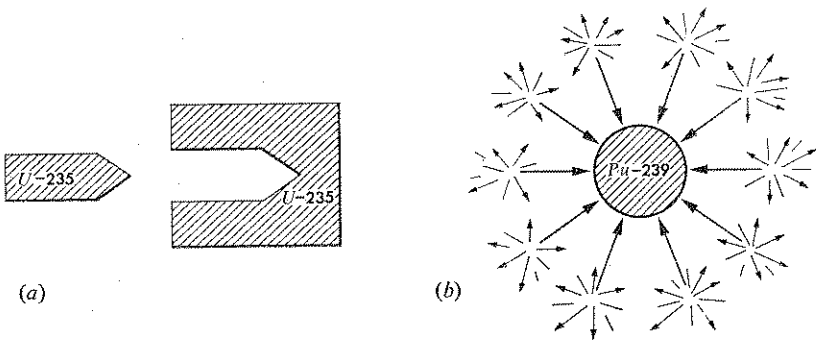


Fig. 70 Fission bombs
(a) *Two small pieces of U-235 combine to become greater than the critical size*
(b) *Chemical explosives surround Pu-239 and compress it to a smaller volume thus increasing the concentration per unit volume of Pu-239*

was initiated within a few millionths of a second after criticality was achieved by spontaneous fission, which a few of the nuclei of both types of fuel will undergo. An upper limit is set to the size of a fission bomb by the practical difficulty of combining more than two sections at exactly the same time, and because each of the sections must be below the critical size so that it can be transported safely.

NUCLEAR REACTORS

Nuclear reactors can be used for two entirely different purposes, namely to make artificial isotopes and as a source of power. Before considering how they can fulfil these functions, let us look at the design of a typical reactor.

11 Structure of a nuclear reactor

In a nuclear reactor for producing a controlled chain reaction, the concentration of the fissionable isotope is usually much less than that in a bomb, i.e. the fuel is not highly enriched; this is for economic reasons only. Therefore careful measures must be taken to conserve the neutrons produced during fission and increase their chances of promoting further fissions.

Slow neutrons have a considerably greater chance of colliding with a nucleus than fast ones in the same way as for other sub-atomic particles (see p. 93). In fact the chance of a slow neutron colliding with a nucleus of uranium-235 is about 500 times greater than that of a fast one. The neutrons released during the fission of uranium-235, however, are fast, so that it is usual to slow them down before they reach further sections of the fuel; this is the function of the moderator.

Moderator

The moderator slows down the neutrons by means of elastic collisions between its atoms and the neutrons, and since a particle is slowed down most effectively by one of equal mass, the atoms of the moderator should be as light as possible; in addition, their chances of absorbing neutrons should be low. Suitable materials are water or carbon in the form of pure graphite; the latter frequently forms the basic structure of the core of a reactor and holds the other components at C as shown in Fig. 71. Typical dimensions for such a structure are about twenty feet.

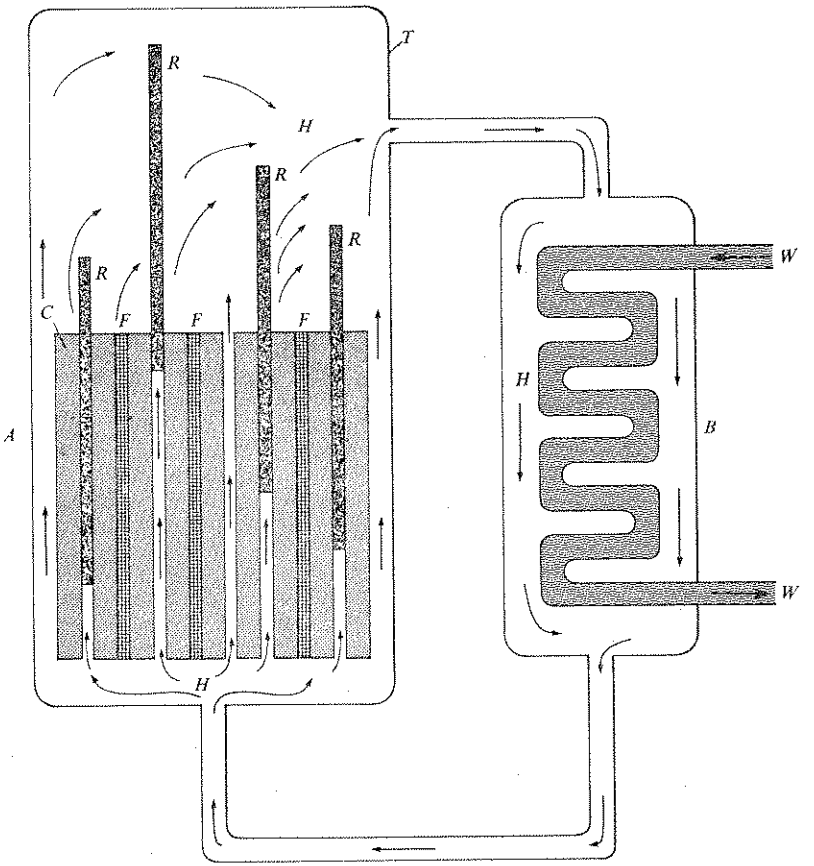
Control rods

Control rods R are used to absorb excess neutrons and thereby prevent the reaction from going too fast; a suitable material is boron-10 which

absorbs neutrons readily, and it is often incorporated in stainless steel,

$$^{10}_{5}\mathrm{B} + {}^{1}_{0}n \rightarrow {}^{4}_{2}\mathrm{He} + {}^{7}_{3}\mathrm{Li}$$

The rods are inserted in the reactor and the speed at which the reactor supplies energy is controlled by careful adjustment of the lengths inserted,



A, reactor core; B, heat exchanger replacing furnace of a conventional power station; C, moderator (carbon)—slows down neutrons; F, fuel rod (uranium)—fissionable; H, coolant (carbon dioxide)—removes heat from reactor; R, control and shut-off rods (boron)—absorbs neutrons; T, pressure chamber; W, water for steam turbines.

Fig. 71 Power supply reactor

(a) *For supplying power the coolant H is heated by the reactor and then heats water W for driving steam turbines*

(b) *For making radioisotopes, the materials to be transmuted are placed in channels in the moderator*

the movement of a single rod through a distance of one inch can alter the performance of the reactor considerably.

In an emergency, if the reactor begins to go too fast, a special set of control rods, known as shut-off rods, drop in automatically; they immediately absorb the neutrons so that the chain reaction stops entirely.

Fuel elements

The uranium fuel F is generally in the form of rods about one inch in diameter which can be inserted in channels in the moderator. In this way the neutrons released during fission can readily reach the moderator, where they are slowed down and then enter further fuel elements. The uranium fuel becomes contaminated by its own fission products, so it has to be purified every few months.

Shield and coolant

Because neutron bombardment has dangerous biological effects, a reactor must be very efficiently shielded, and walls of concrete about seven feet thick are fairly typical.

The energy is released inside the reactor in the form of heat which must be extracted if it is to be used, and extraction is the function of the coolant H. For this purpose carbon dioxide can be made to circulate through the channels in the graphite moderator which carry the control rods or fuel elements. Since the coolant reaches the outside of the shield it is important that the material selected should not become radioactive under neutron bombardment.

12 Manufacture of artificial isotopes

Isotopes are made in a nuclear reactor by subjecting different elements to intense bombardment by neutrons some of which are likely to be captured by the nuclei. One of the first large reactors for this purpose was built at Harwell in 1948, and it is still supplying radioisotopes such as sodium-24 on a large scale. The materials to be bombarded are placed in small aluminium cannisters about two inches long and are inserted in channels inside the moderator which are indistinguishable from those carrying the fuel rods. There they are subjected to neutron bombardment at the rate of up to 10^{12} neutrons cm^{-2} sec^{-1}. The heat energy produced in this type of reactor is often wasted.

One particular isotope made by neutron bombardment of uranium-238 in a reactor is the element plutonium, which is an alternative to uranium-235 as a fissionable fuel, not found naturally in any appreciable quantity:

$$^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{93}\text{Neptunium} + {}^{0}_{-1}e \text{ and } {}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e$$

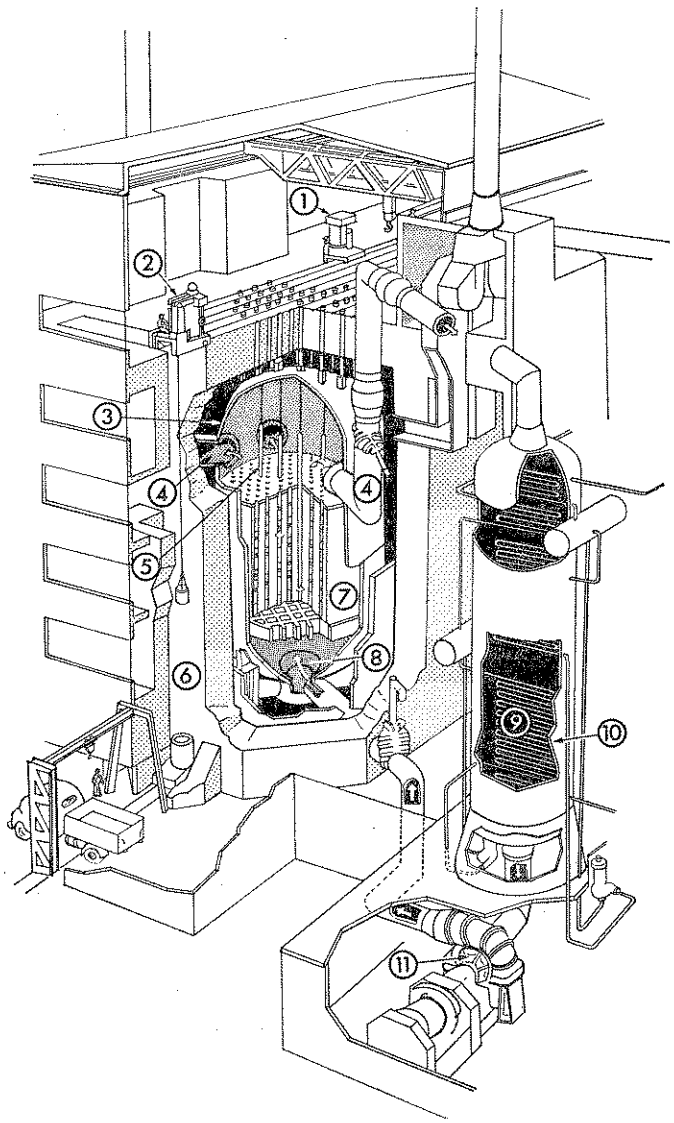


Fig. 72 Calder Hall Reactor. First commercial reactor for generating electricity

Plutonium is made in large quantities in reactors which are known as breeders, so called because they manufacture plutonium fuel more rapidly than they use up their own fuel, U-235. The plutonium is then extracted and can be used in other reactors.

walls of the tube, the beam is found to become unstable in direction, developing a 'wiggle' as shown in Fig. 73*b*. In an attempt to overcome this instability, magnetic fields of various shapes have been applied and have met with varying degrees of success. Much work is being done along these lines at the present time and this is considered to be of such world-wide importance that it is being carried out by international teams and is non-secret.

16 Supernovae

An interesting natural phenomenon which may result from fusion and fission is the occurrence of supernovae. These are very bright stars which suddenly appear at irregular intervals of a few hundred years and then lose their brightness, dropping to half their intensity in a period of about 56 days. A half-life period of 56 days is found for an artificially produced element called californium ($^{254}_{98}$Cf) which disintegrates by spontaneous fission. A possible explanation for supernovae is that californium is somehow made, perhaps by fusion processes, and then disintegrates by spontaneous fission, giving out enormous quantities of energy of which some is visible. Since the number of atoms of californium will be halved after 56 days the intensity of the energy radiated by the fusion will also be halved.

Problems on Chapter Nine

1. The radiation from the sun is such that the earth receives 0·14 joules per sq cm per second. Calculate the rate at which the sun loses mass, given that the distance of the earth from the sun is $1{\cdot}5 \times 10^{13}$ cm and the velocity of light in vacuo is $3{\cdot}0 \times 10^{10}$ cm per sec.
2. Calculate the average binding energy per nucleon of helium-4 and nitrogen-14 from the following data: mass of proton = 1·00727; mass of neutron = 1·00866; mass of electron 0·00055; atomic masses of helium and nitrogen = 4·00260 and 14·00307 respectively, all in a.m.u.
(1 a.m.u. = 931 MeV.)
3. Calculate the approximate mass of uranium which must undergo fission to produce the same energy as 100 tons of coal. Assume that 1 ton = 10^6 g; heat of combustion of coal = 8 000 calories per gramme; 1 calorie = 4 joules. 1 fission process of uranium-235 releases 200 MeV; 1eV = $1{\cdot}6 \times 10^{-12}$ erg; Avogadro's number = $6{\cdot}0 \times 10^{23}$ atoms per gram-atom.

4. 'The helium nucleus has a mass number 4 but its mass is only 3·9715 times that of a hydrogen nucleus.'
Comment on the significance of this statement. L 63 II–12 (part)
5. Write short notes on the thermonuclear process. L 61 II–12 (part)
6. Give a brief account, indicating some practical applications of (i) nuclear fission, (ii) the thermonuclear process. L 64A II–12
7. The following equation represents a nuclear fission process:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U} \rightarrow ^{90}_{38}\mathrm{Sr} + ^{143}_{54}\mathrm{Xe} + 3^{1}_{0}\mathrm{n}$$

What is meant by nuclear fission? Explain the source of energy released during the process represented by the above equation.
8. What is a controlled nuclear chain reaction? Describe how this can be achieved, indicating briefly the function of each part of the reactor.

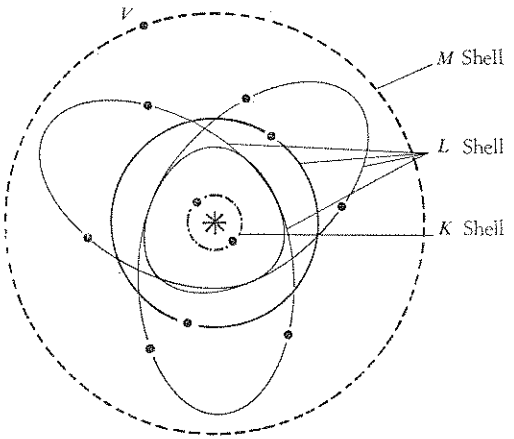
Chapter Eleven

Atomic Structure: The Arrangement of Electrons in the Atom

1 General

The chemical element which an atom constitutes, as has already been mentioned, depends upon the positive charge that it carries and this is equal to the atomic number Z in electronic units. Since the atom as a whole is neutral, it must also contain Z electrons.

The positive charge of the atom resides in a very small nucleus, as was confirmed by the alpha particle scattering experiment of Rutherford (see p. 83), but the experiment gave no indication as to how the electrons are distributed. We saw in the last chapter that Bohr made the assumption that electrons can move only in certain well-defined orbits each of which is associated with a particular level of energy. Bohr's conception was soon extended by Sommerfeld to include elliptical as well as circular orbits, as shown in Fig. 77.



K-shell $n=1$, 1 possible orbit
L-shell $n=2$, 4 possible orbits
M-shell $n=3$, 9 possible orbits (only one is normally occupied)
V, valency electron

Fig. 77 Sodium atom (atomic number = 11) showing orbits normally occupied. The three elliptical orbits in L-shell have equal energies

2 Orbits and shells

The permissible orbits of the Bohr model of the atom can be grouped together into *shells* and these are designated alphabetically starting with the letter K for the one nearest to the nucleus (Fig. 77). Each of these shells is associated with a number n, known as *the principal quantum number*; thus for the K-shell, $n=1$; for the L-shell, $n=2$, and for the M-shell, $n=3$, etc. The value of n for the shell to which an orbit belongs is the first factor in determining the energy of the orbit, because it determines how near its electrons are to the nucleus, thus an electron in the L-shell has in general less energy than one in the M-shell.

The *shape* of the orbit, i.e. the eccentricity of the ellipse, also influences the energy of its electrons because it affects the proximity with which the electrons approach the nucleus and other electrons and the way they are influenced by them. The variety in the shapes of the orbits results in a good deal of overlapping between energies in different shells, particularly for those whose principal quantum numbers are large.

Some orbits differ only in *direction*, and these are normally associated with the same energies. For example, in the L-shell of the sodium atom (Fig. 77) there are three elliptical orbits all having the same energy and also a circular orbit with a slightly different energy. Thus the L-shell contains four different orbits but only two different energy levels. (The direction of the orbit becomes significant if the atom is placed in a magnetic field; see *Zeeman effect* in the glossary.)

3 Electron distribution in an atom

Electrons are distributed in a definite way among the orbits. In order to explain the distribution we need to consider a further assumption which stems from a principle put forward by Pauli†: *it is never possible for an orbit to hold more than two electrons.*

In addition it is found that each shell has a specific number of orbits grouped in it, this number being equal to n^2, where n is the principal quantum number; thus the L-shell ($n=2$) contains 4 orbits and the M-shell ($n=3$) contains 9 orbits. Hence the maximum number of electrons that a *shell* can hold is $2n^2$. The numbers of orbits and electrons in the various shells are given in the table on the next page.

We shall see that the numbers in the right-hand column are significant when considering the chemical behaviour of atoms and their positions in the periodic table of elements.

† See glossary, page 303.

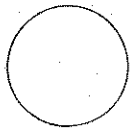
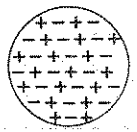
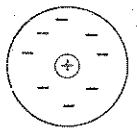
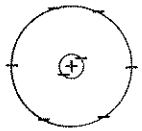
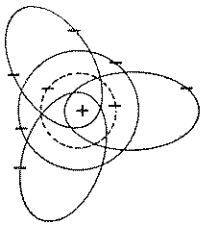
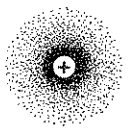
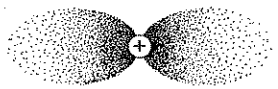
	ATOMIC MODEL	APPLICATIONS
	Billiard ball, Dalton, 1803	Kinetic theory of gases
	Plum pudding, Thomson, 1897	Historical interest only
	Nuclear, 1911	Superseded by Rutherford–Bohr
	Rutherford–Bohr (showing shells only), 1914	Penetration of matter by small particles. Radioactivity and nuclear energy
	Rutherford–Bohr (showing separate orbits), 1914	Emission of e-m spectra (in simple cases)
	Electron cloud (≡circular orbit)	Emission of e-m spectra Molecular structure
	Electron cloud (≡elliptical orbit)	ditto

Fig. 79 Atomic models and their uses

whereas the Bohr model is concerned with *distance* from the nucleus. It can be shown that for the first orbital, which is a solid sphere of varying

density, the most likely distance at which to find an electron is the same as the radius of the first Bohr orbit, so that the two models are compatible with one another.

7 Periodic classification of elements

When elements are put in order of increasing atomic number it is found that they can be arranged in a table as shown on pp. 182–3 in which elements with similar chemical properties appear one below another. The atomic number, Z, is the positive charge in the nucleus and so is equal to the number of protons and also to the number of electrons in the neutral atom. It will be seen that the table takes no account of the number of neutrons in the atom, and atoms with differing numbers of neutrons but the same number of protons occupy the same place in the table, hence the name *isotope* meaning 'same position'.

The arrangement of the electrons in the various shells when the atom is in the ground state is given in italics in the table, and from these figures the following observations can be made.

a The frequency with which the numbers 8, 18, 32 occur indicates that a shell is very stable when it holds these numbers of electrons, even if it is not completely filled by them. (It should be noticed in passing that these are the same as the numbers of electrons that fill the L-, M-, and N-shells respectively—see the table on p. 178. Thus an additional electron often goes to the next higher shell in preference to filling further orbits in the lower shell, e.g. potassium and calcium, atomic numbers 19 and 20, have electrons in the N-shell although some of the orbits of the M-shell are not filled.

b Elements with 8 electrons in their outermost occupied shell are all normally gases and are called *inert gases* because of their reluctance to form compounds. This is accounted for by the difficulty of disturbing the arrangement of 8 outer electrons, which must therefore be a particularly stable configuration.

8 Valence electrons

c When the number of electrons in the outermost occupied shell of an atom is a little less than 8, then the atom can readily accept electrons to bring the total up to 8 and it thereby acquires a structure like that of an inert gas, which is very stable. For example oxygen has 6 electrons in its outermost occupied shell, and it can accept 2 further electrons thereby making a negative ion which has 8 electrons in its outermost shell. Alternatively, if the number of electrons in the outermost

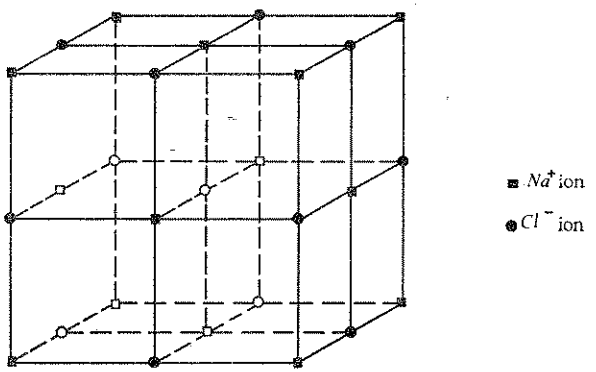


Fig. 82 Sodium chloride crystal. (In reality ions are large enough to touch each other)

Another way in which atoms can combine, known as *co-valent* (or *homopolar*) bonding, is by sharing some of their electrons in order to produce outer groups of eight. An example of such bonding is the molecule of chlorine Cl_2, in which two of the electrons are shared, thereby surrounding each ion with eight electrons (Fig. 83).

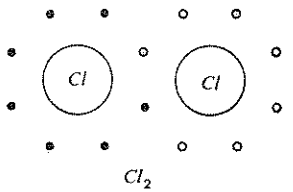


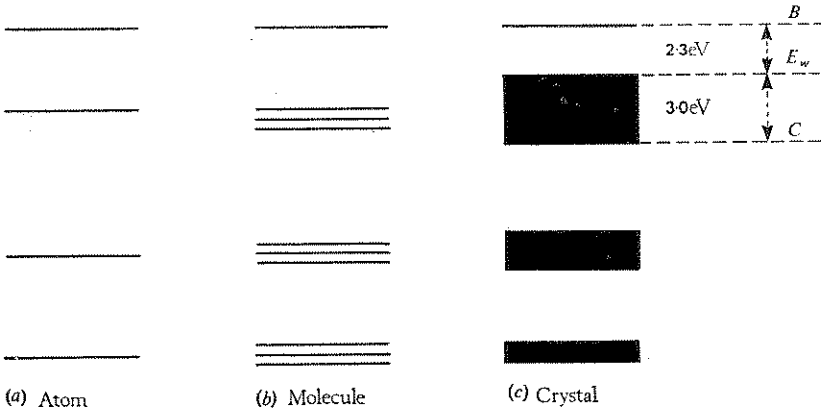
Fig. 83 Co-valent (homopolar) bonding. Some electrons shared

***11 Energy levels in molecules**

The intimate association of atoms in molecules results in the energy levels of the component atoms being modified. A single level in the atom is replaced by a group of several levels lying very close together (Fig. 84 *a, b*) and the number of levels in each group depends upon the complexity of the molecule. Thus for each possible energy in an isolated atom there are two or more possible energies when the atom forms part of a molecule.

***12 Energy levels in crystals**

The atoms of a crystal lie very close to one another and this again modifies the permissible energy levels of the electrons. Each level corresponding to



B, free electrons; C, conduction band; E_W, work function. For sodium work function = 2.3 eV; conduction band width 3.0 eV.

Fig. 84 Energy levels in atom, molecule and crystal. In molecule number of levels increases with complexity of molecule. In crystal each level spreads into continuous band of possible energies

a single energy in an isolated atom is broadened into a continuous band when the atom forms part of a crystal so that the electrons can have a range of possible energies as shown in Fig. 84*c*. Each band can hold a maximum of two electrons per atom.

An important difference between a conductor and an insulator is that the uppermost band of an insulator holds its full quota of two electrons while that of a conductor holds only one. The outer electron in a conductor can therefore receive a small quantity of energy while remaining in the same continuous band and this energy can enable the electron to pass from one atom to another since the corresponding band in the neighbouring atom is not fully occupied, so that the electrons can move freely between the atoms of a crystal. This upper band is called the *conduction band*. In an insulator, on the other hand, an electron can only move to a neighbouring atom if it is given enough energy to jump to a higher level since its own level in the neighbouring atom is fully occupied by two electrons.

13 Work function

The outer or 'conduction' electrons in a metal can be considered as belonging to the crystal structure as a whole rather than to individual atoms; they move freely inside the metal with a range of energies equal to the width of the conduction band shown in Fig. 84*c* and they are held inside

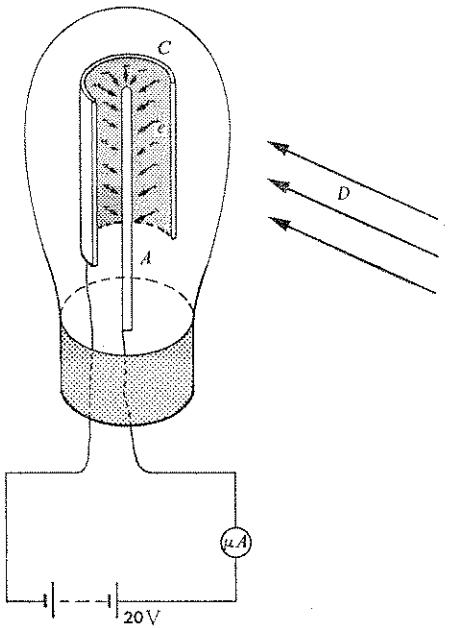
an atom containing unpaired electrons, and also to the spacing of the atoms being such that their influence upon one another sets their axes parallel in one locality or domain.

PHOTO-ELECTRIC EMISSION

When radiation falls on some solids, and in particular on metals, the latter are found to emit electrons; this is known as the *photo-electric effect.* It can be studied using a photo-cell and circuit as shown in Fig. 87.

6 Photo-cell

A photo-cell consists of a cathode surface on to which light is directed, and an anode in the form of a wire which does not interrupt the passage of the light, the two electrodes being placed in a glass envelope which is evacuated to allow the free passage of electrons. A small potential difference, typically about 20 volts, is applied between the electrodes so that all the electrons emitted by the cathode are attracted to the anode, and the anode current then indicates the number of electrons emitted per second; this can be measured by means of a microammeter.



A, anode; C, cathode; D, incident light; *e*, electrons emitted from cathode.

Fig. 87 Photo-cell. Radiation falling on cathode releases electrons

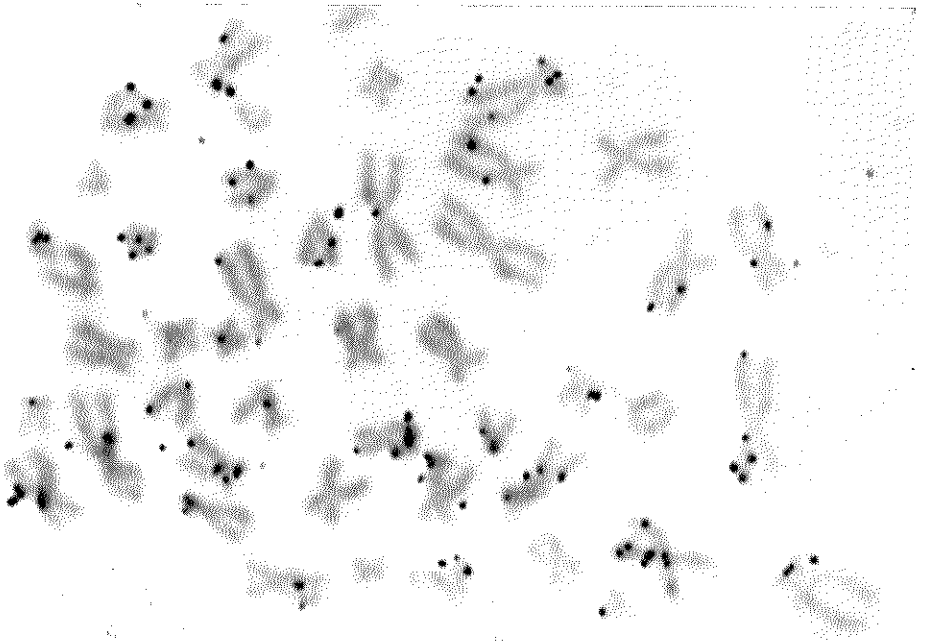
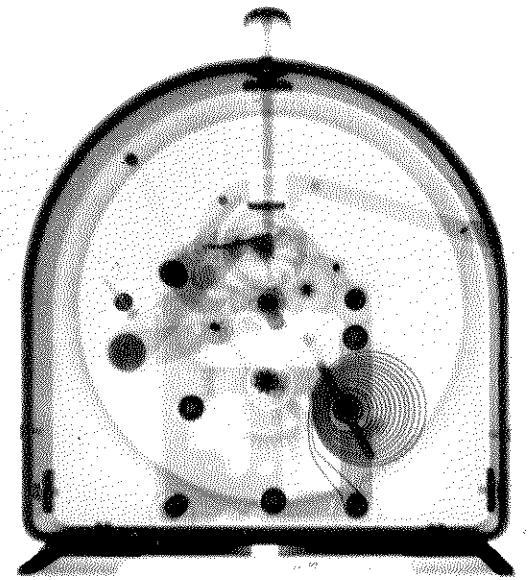


Plate 8 Autoradiograph of human chromosomes labelled with hydrogen-3. The chromosomes are from white blood corpuscles and were grown in a culture containing hydrogen-3; black dots indicate positions of individual hydrogen atoms (p. 140). Magnification × 1 000.

Plate 9 Gieger-Müller tube, actual size (p. 115).

Plate 10 Gamma ray photograph of stop-clock using thulium-170 (p. 142).



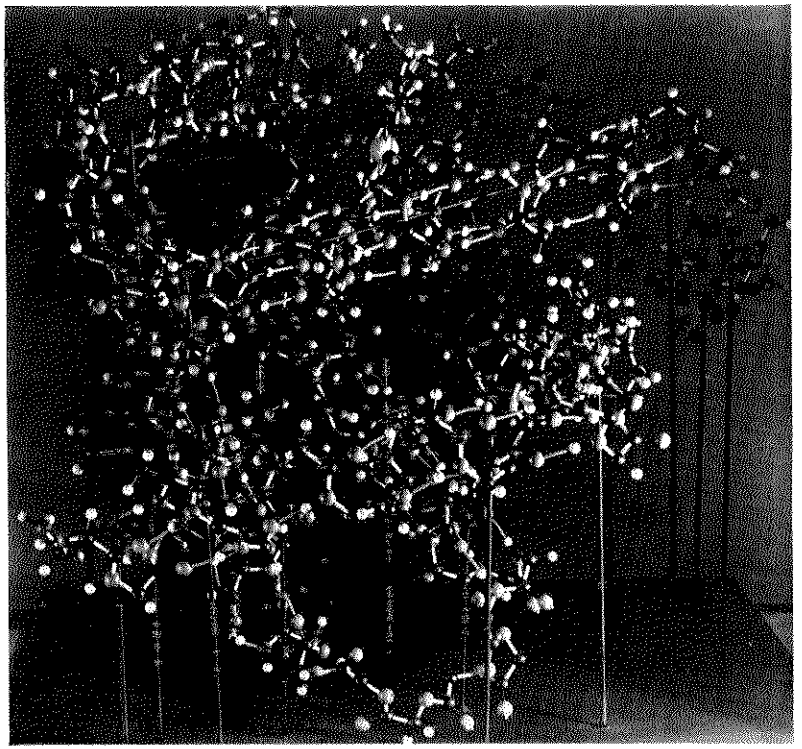


Plate 11 Myoglobin molecule analysed by X-rays. This structure was the first of the large organic molecules to be established (p. 215).

Plate 12a X-ray diffraction by zinc oxide powder (1·5 Å). Crystals in the powder are orientated in all directions; some of them will be inclined to the X-ray beam at the Bragg angle. Each circle corresponds to a particular Bragg angle and hence to a particular set of planes (p. 237).

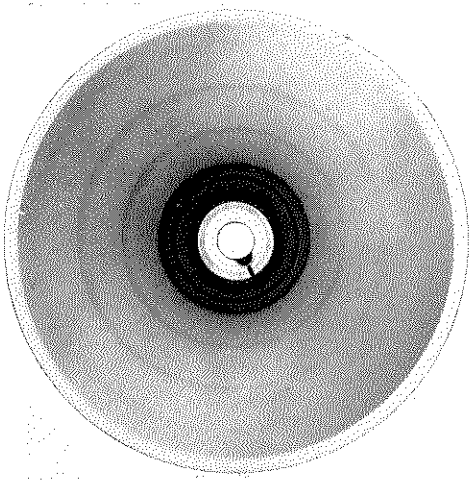
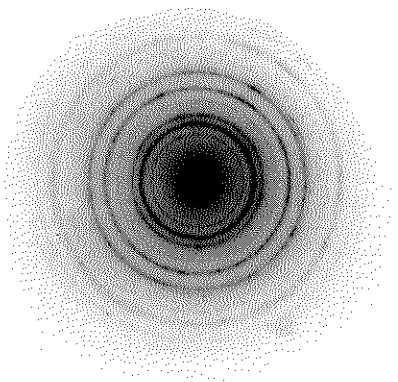


Plate 12b Electron diffraction by cuprous oxide powder (75 kV). The similarity between these patterns shows that beams of electrons can behave like waves.



7 Experimental results

Using the circuit shown in Fig. 87 with monochromatic light of different known frequencies, the following results are obtained:

a Electrons are emitted only if the radiation falling on the cathode has a frequency greater than some critical value ν_0 known as the *threshold frequency*. The wavelengths must therefore be less than some critical value, (see Fig. 88).

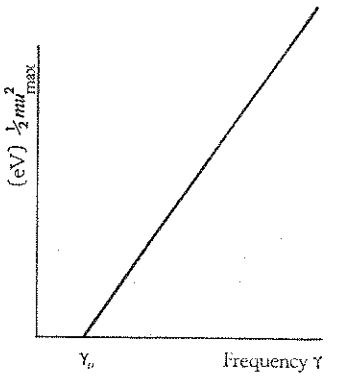


Fig. 88 Maximum energy of electrons emitted: frequency of incident radiation. $h\nu = h\nu_0 + \frac{1}{2}mu^2$. *Gradient of graph* = h (*Planck's constant*) *No electrons are emitted for radiation below threshold frequency* ν_0

b The threshold frequency is characteristic of the metal of which the cathode is made.

c The number of electrons emitted per second by monochromatic light is proportional to the intensity of the light. Since the number of electrons emitted is measured by the current in the anode circuit, the law is demonstrated by plotting the photo-electric current against the intensity of the light; this gives a straight line through the origin as shown in Fig. 89.

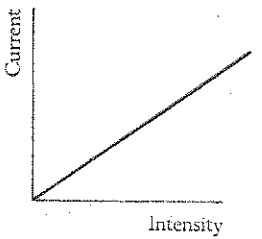


Fig. 89 Photo-electric current: intensity of monochromatic light. Number of electrons emitted is proportional to number of incident photons

d If monochromatic light of frequency ν is used, then the maximum velocity u with which electrons are emitted is given by

$$h\nu - h\nu_0 = \tfrac{1}{2}mu^2,$$

where h is Planck's constant and ν_0 is the threshold frequency; this is called *Einstein's photo-electric equation* and it is shown graphically in Fig. 88.

This last relationship can be demonstrated using monochromatic light of known frequency and applying to the anode of the photo-cell a negative voltage, $-V$, whose magnitude is adjusted until the anode current is just cut off; the electrons will overcome the electrical repulsion and reach the anode only if they are emitted with a kinetic energy greater than eV, i.e. if $\frac{1}{2}mu^2 > eV$, and hence by measuring the voltage, V, at which the current is cut off, the maximum velocity, u, of the electrons can be determined.

It is found that for most metals the threshold frequency lies in the ultra-violet region of the spectrum so that no electrons are emitted using visible light which has a lower frequency. However, for alkali metals the threshold frequency lies in the visible region, while for caesium it is in the infra-red; thus caesium is sensitive to the whole of the visible spectrum.

8 Explanation of the photo-electric effect

Electrons are released from the metal by the impact of photons and it is assumed that each electron requires one photon for its emission.

In order to release an electron an energy of at least E_W is required where E_W is the work function and is characteristic of the metal (see p. 187 and Fig. 84*c*). This can be supplied by a single photon provided that the energy $h\nu$ is greater than E_W. Hence the minimum or threshold frequency is given by $h\nu_0 = E_W$, and is therefore characteristic of the metal (see paragraphs *a* and *b* of section 7).

Since each electron requires one photon for its emission, the number of electrons emitted is proportional to the number of photons falling on the cathode, i.e. the number of electrons emitted per second is proportional to the intensity of the incident light (see paragraph *c* of section 7).

If the photon of monochromatic light has an energy greater than that required to release an electron, then the excess energy is imparted to the electron in the form of kinetic energy. For electrons having the maximum permissible energy inside the metal, this may be expressed in terms of the work function:

$$h\nu - E_W = \tfrac{1}{2}mu^2$$

since $E_W = h\nu_0$ we get $h\nu - h\nu_0 = \frac{1}{2}mu^2$,

which is Einstein's photo-electric equation. For electrons having less than

the maximum energy inside the metal, the kinetic energy on emission will be slightly less so that the above equation gives the *maximum* velocity with which an electron can be emitted.

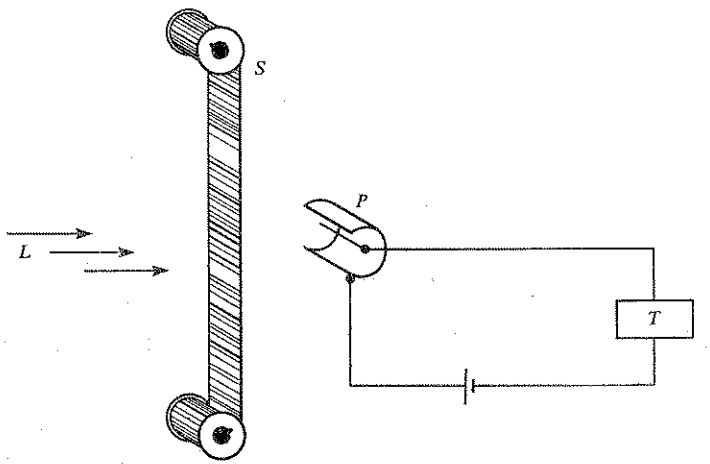
9 Applications of the photo-electric effect: an illumination meter

A light meter, or photometer, consists of a photo-cell connected to a galvanometer which can be calibrated to read intensity directly. To calibrate such a photometer, a light source of intensity I_0 is placed at different known distances d from the photo-cell and the corresponding readings taken. Then, using the inverse square law, the intensity of illumination $= \frac{I_0}{d^2}$, where I_0 is an unknown constant; for absolute values, a source of known intensity I_0 must be used.

With the aid of suitable amplifiers a photo-cell can be made into an extremely sensitive laboratory instrument for detecting light. It is, however, inconvenient for ordinary photography since it requires a battery for its operation, and for this purpose a photo-voltaic cell may be used which works on a slightly different principle, namely that the incident light generates an e.m.f. (p. 269).

10 Film sound track

The sound track of a film moves steadily between a photo-cell and a light source as shown in Fig. 90, and the output from the photo-cell is amplified



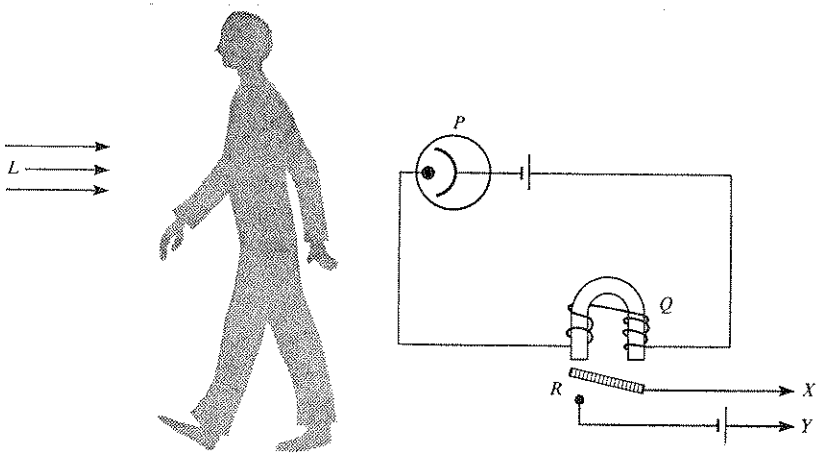
L, light source; P, photo-cell; S, sound track of film; T, loudspeaker.

Fig. 90 Sound track of film. Variations in light intensity reaching photo-cell result in variations in current through loudspeaker

and fed to a loudspeaker T. A typical track is shown at S in Fig. 90: when the lines on the track are close together the current variations will be rapid as the film moves past the photo-cell, giving a high pitched note; when there is a large contrast between light and dark lines then greater variations in current will be produced, giving a louder note.

11 Automatic door

An automatically opening door is controlled by a relay switch (R in Fig. 91) which is held open by an electromagnet supplied with current from a photo-cell. If the shadow of a person cuts the light off from the photo-cell, the current to the electromagnet is cut off momentarily; the relay switch then completes the circuit which operates the door mechanism, and it remains in this position until the door is fully open. A burglar alarm works on a similar principle but in this case the break in the current from the photo-cell causes a circuit to be completed which makes a bell ring until it is re-set by hand.

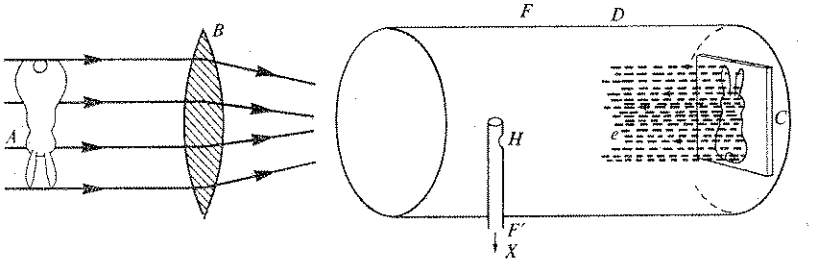


L, light source; P, photo-cell; Q, electromagnet; R, relay switch; XY, to door mechanism.

Fig. 91 Automatic door. When light to photo-cell is interrupted, current to electromagnet stops and relay switch R closes

12 Television camera

A television camera incorporates a special form of photo-cell. In one type of camera, illustrated in Fig. 92, an image of the scene is focused on to a photo-sensitive surface C. The surface emits electrons in proportion to the brightness of the image at a given point, and the beams of electrons



A, light from scene to be photographed; B, lens to focus image on to cathode; C, photo-cathode receives optical image and emits electrons; D, evacuated cylindrical tube; *e*, electron beams; F, F′, plane in which 'electron image' is formed; H, small hole receiving electrons; X, electrons fed to transmitter.

Fig. 92 Television camera

from each element of the picture are focused to produce an 'electron image' of the scene in the plane FF′ in the diagram. The beam is focused by a magnetic field derived from a current in a solenoid surrounding the whole tube, the details of which are outside our present scope.

The electrons must then be fed into a small aperture H and sent to the transmitter. In principle, the aperture could be made to scan the electron image (like the eye scans a page of a book) but in practice it is easier to keep the aperture fixed and move the whole electron image past it; this is accomplished by means of magnetic fields at right-angles to the electron beams (not shown in the diagram). As the image crosses the aperture, electrons pass through it in proportion to the brightness of the corresponding point of the optical image, and the electron current thereby produced is amplified and passed to the transmitter. Once there it modulates the radiations sent out, and in this way a signal is transmitted to the receiver, which is used as described on p. 70.

SPECTRA

13 Visible spectra

The complete electromagnetic spectrum can be divided into different regions according to the wavelength (or the frequency) as shown in Fig. 93. The visible region consists of radiation having wavelengths extending from approximately 4×10^{-5} centimetres for violet light to $7{\cdot}5 \times 10^{-5}$ centimetres for red light, and these wavelengths correspond to photons having energies of a few electronvolts.

Visible light can be separated into the different wavelengths by means of a spectrometer and the spectra formed thereby can be one of several types.

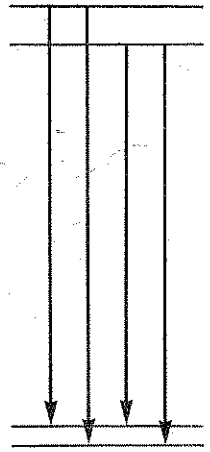


Fig. 97 Emission by electron transitions in molecule. Several wavelengths are emitted which are almost equal

lines which are so close together that they look like continuous bands. Such a spectrum is emitted when electrons in excited *molecules* return to the ground state. As we saw on p. 186 and in Fig. 84*b* the energy levels of atoms in molecules fall into groups having values nearly equal to one another and therefore when electrons jump between pairs of levels in two specified groups, they emit photons whose energies differ only slightly from one another, so that sets of nearly equal lines are observed (see Fig. 97).

X-RAYS

19 Introduction

X-rays were discovered inadvertently by Röntgen in 1895 when he noticed that a low pressure discharge tube covered with opaque black paper caused fluorescence on a screen; this could not be accounted for by any radiations known at that time and he therefore named these unknown rays *x*-rays.

Later work has shown that X-rays are electromagnetic radiation and that X-ray spectra differ from those of light in that the wavelengths are much shorter, typically 10^{-8} centimetres, and the photons are of correspondingly higher energy, $\sim$10 keV.

20 X-ray line spectrum

An X-ray line spectrum is emitted when electrons drop to the inner shells

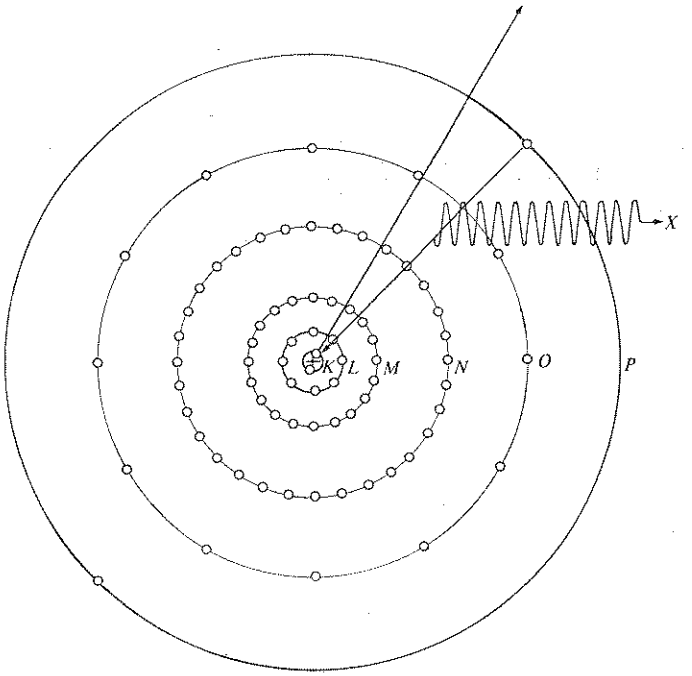


Fig. 98 X-ray emission by tungsten atom. Electron removed from inner shell is replaced by electron from outer shell. Large energy change causes emission of X-ray photon

of atoms, usually the K-shell or the L-shell, provided that the transitions produce photons which are large enough to be in the X-ray region. This is possible for all atoms except those which are lighter than sodium. (Fig. 75 shows the relative values of the energy levels in hydrogen and sodium atoms and indicates how much smaller are the transitions in hydrogen.) In order that X-rays are emitted, therefore, an electron must first be removed from an inner shell of a fairly heavy atom, and this can be done by the impact of fast-moving electrons having an energy of about 20 keV; the gap in the inner shell is then filled by one of the outer electrons and the transition results in the radiation of a photon of high energy (Fig. 98).

21 X-ray continuous spectrum

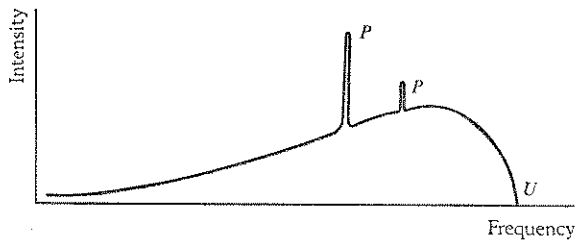
An X-ray continuous spectrum is emitted by free electrons, such as those in cathode rays, which are moving fast and are suddenly slowed down

by impact with matter from a velocity of u_1 to u_2. The loss in kinetic energy of an incident electron is transformed directly into a photon of frequency given by $h\nu = \frac{1}{2}mu_1^2 - \frac{1}{2}mu_2^2$, and since u_2 can have any value less than u_1, a continuous spectrum is emitted. The maximum frequency is emitted when an electron is brought to rest, hence $h\nu_{max} = \frac{1}{2}mu_1^2$.

In a tube for the production of X-rays, both the above processes take place simultaneously so that both a line and a continuous spectrum are emitted.

22 Production of X-rays

In an X-ray tube a beam of fast-moving electrons strikes a suitable target, such as a piece of tungsten; some of the electrons in the incident beam will remove electrons from the inner shells of the atoms of the target and then transitions within the atoms will cause the emission of the X-ray spectrum characteristic of tungsten. At the same time some electrons in the incident beam will be slowed down rapidly by their impact with the target, thereby emitting a continuous spectrum. Thus a typical energy distribution takes the form shown in Fig. 99 in which a line spectrum, P, characteristic of the target is superimposed on a continuous spectrum; the maximum frequency emitted, U, is limited by the kinetic energy of the electrons in the incident beam according to the relation $h\nu_{max} = \frac{1}{2}mu^2$, and since the kinetic energy is equal to eV, where V is the potential difference applied across the tube, $h\nu_{max} = eV$; the output from an X-ray tube is often described in terms of this voltage.

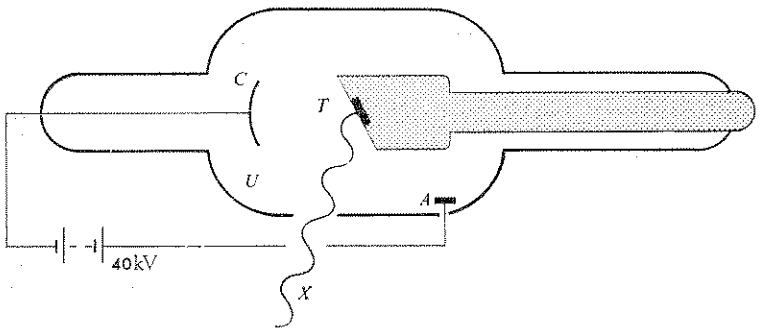


P, peaks resulting from line emission of target material; U, upper frequency limit governed by potential difference across tube.

Fig. 99 Output from X-ray tube

*23 X-ray tube: Röntgen type

A tube for the production of X-rays, shown in Fig. 100, was designed by Röntgen and is essentially a low pressure discharge tube having a concave cathode C and a tungsten target T situated at its centre of curvature.



A, anode; C, cathode (cold); T, target (tungsten embedded in copper); U, air at low pressure (10^{-4} centimetres mercury); X, X-rays.

Fig. 100 Röntgen X-ray tube (cold cathode). Wavelength and intensity of emission both depend upon air pressure inside tube

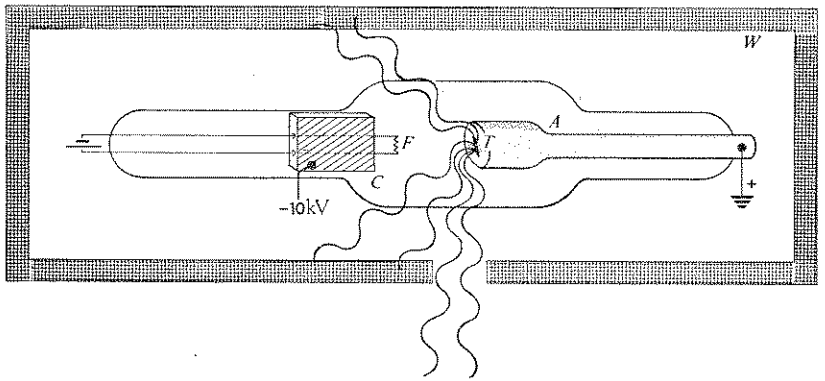
The electrons in the cathode rays converge on to the target which absorbs their energy and then emits X-rays in all directions. The position of the anode A is unimportant and is often located at the side. A high voltage is required to operate this tube, a typical value being 40 kV for a tube at a pressure of 10^{-4} centimetres of mercury, which is about the lowest pressure at which a tube of this type can operate.

A serious limitation to this type of tube is that for a given pressure neither the intensity nor the frequency of the X-rays can be varied. The reasons for this are as follows: the pressure in the tube determines the voltage needed to maintain a discharge; since this is the voltage through which the cathode ray electrons are accelerated, it controls the maximum frequency of the continuous spectrum emitted ($h\nu = eV$) so that the frequency depends ultimately upon the pressure. In addition, the pressure determines the number of positive ions in the tube, this controls the *number* of cathode ray electrons released and this, in turn, controls the number of X-ray photons, i.e. the intensity of the radiation. Thus the intensity of the radiation is also ultimately dependent upon the pressure.

The Röntgen tube, therefore, lacks versatility, and the frequency and intensity are interdependent, both being governed by the pressure. This difficulty is overcome in the Coolidge type of tube.

24 X-ray tube: Coolidge type

Most modern X-ray tubes are of the Coolidge type, as shown in Fig. 101. A filament F is heated so that it emits a beam of electrons; the electrons are concentrated on to a tungsten target T which absorbs their



A, copper anode; C, cathode (shapes field); F, filament (emits electrons when hot); T, tungsten target (emits X-rays); W, lead shield (protects personnel).

Fig. 101 Coolidge X-ray tube (hot filament). Wavelength controlled by potential difference across tube. Intensity controlled by temperature of filament

energy and converts some of it into X-rays. The intensity of the X-rays, i.e. the number of photons emitted, is governed by the number of electrons which strike the target and hence by the temperature of the filament. The maximum frequency of the X-rays is adjustable within certain limits because it depends upon the voltage applied ($h\nu = eV$) and this can be varied over a wide range—from 500 V to 10 MV or more. (This wide range is made possible by the very high vacuum at which a tube of this type can operate, which is typically 10^{-6} centimetres of mercury.) Thus the frequency depends upon the applied voltage while the intensity depends upon the heating current, both of which can be varied between fairly wide limits. The tube is therefore versatile.

X-rays are emitted from the target in all directions, but the whole tube is surrounded by a thick shield of lead W in which there is a small window so that the rays are only allowed to leave in one direction and those emitted in all other directions are absorbed by the shield.

The filament from which the electrons emanate is a thin wire and behind it lies the cathode C whose function is to shape the electric field so that it concentrates the electrons on to the target. Three further factors to be considered in the design of a tube are insulation, dissipation of heat, and size of target.

Insulation

The potential difference to be applied across the tube is determined by

the depth to which the X-rays are required to penetrate since high energy X-rays have a greater penetrating power, and the voltage needed may be several million volts. For such tubes the electrodes must be well separated, so in practice the size of a tube varies from 40 feet for deep X-ray therapy to a few inches for dental photography. High voltage tubes are often immersed in oil to safeguard the operator and to prevent damage to the tube itself from these very high voltages.

Dissipation of heat

About 99 per cent of the energy of the incident electron beam is converted into heat; elaborate precautions must be taken, therefore, to prevent the target from becoming too hot—as an illustration, the kinetic energy from an electron beam for a medium sized X-ray tube (15 mA, 400 kV) would boil a litre of water in one minute. The target is often of tungsten which can withstand high temperatures without melting, and it is embodied in a solid block of copper to conduct the heat away to the outside of the tube; sometimes tubes are cooled by water circulating near the target. In addition, a 'linear' target is often used as described below.

Size of target

The target acts as the source of X-rays and it is desirable that its area should be small when used for photography which depends upon the formation of shadows, because sharp shadows are produced by a small source. A small target is also desirable for radiation therapy because it enables the direction of the beam leaving the tube to be precisely defined by using a single small aperture in the shield. But a small target becomes very hot. One method of overcoming these opposing requirements is to use a 'linear' target which is long and narrow and is set at such an angle that it is foreshortened when viewed from the direction in which the rays emerge, as shown in Fig. 101. A typical target of 2 mm × 16 mm inclined at 10° acts as a source of area 2 mm × 2 mm but the heat from the incident electron beam is spread over the whole of its area.

25 Properties of X-rays

X-rays are electromagnetic waves, having a wavelength of between 10^{-7} centimetres and 10^{-10} centimetres or less. Their wavelengths overlap with those of gamma rays ($\sim 10^{-9}$ centimetres) so that the two types of radiation are often identical and differ only in the way in which they are produced—gamma rays originate from the nucleus of an atom, whereas X-rays usually originate from the electron structure of an atom.

spaced scattering points which are separated by suitable distances, and the diffraction pattern obtained depends upon the relative positions of these scattering points. X-ray diffraction by crystals depends upon the regularity with which the atoms are arranged, which is a characteristic of all crystals; the atoms are arranged in identical groups or 'units', and the units as a whole are arranged in a regular pattern. (A unit may consist of a single molecule, e.g. in a crystal of sodium chloride, Fig. 82, a unit is comprised of one atom of sodium and one of chlorine—more strictly ions—or a unit may consist of several molecules, such as that of quartz which consists of three molecules of silicon dioxide.)

*30 Theory of X-ray diffraction

When X-rays are incident on a crystal, we can consider that they are scattered at a single point inside each crystal unit—this is analogous to considering that all the weight of a body acts at the position of its centre of gravity. In Fig. 102 each dot represents the position of the scattering point in a crystal unit, and because the units are arranged in a regular pattern the scattering points lie in parallel planes such as those marked by dotted lines; the diagram shows a cross-section of a solid crystal so that each line represents a plane in the crystal.

Let us consider a beam of X-rays which strikes units A, B, C, etc., lying in the same plane (Fig. 102*a*). At the instant that it strikes the unit A the wavefront is AA_1 and this implies that the waves are in phase at all points on AA_1. New wavefronts will be formed in positions such as CC_1 at which the waves are still in phase with each other, and therefore the waves from all points on AA_1 must have travelled through equal distances to reach CC_1;

$$\text{therefore } AC_1 = A_1C$$

For this consideration to hold, the incident and scattered rays must make equal angles x with the plane containing A, B, C.

(Proof: $\triangle AC_1C \equiv \triangle CA_1A$

because right angle $\angle AC_1C$ = right angle $\angle CA_1A$

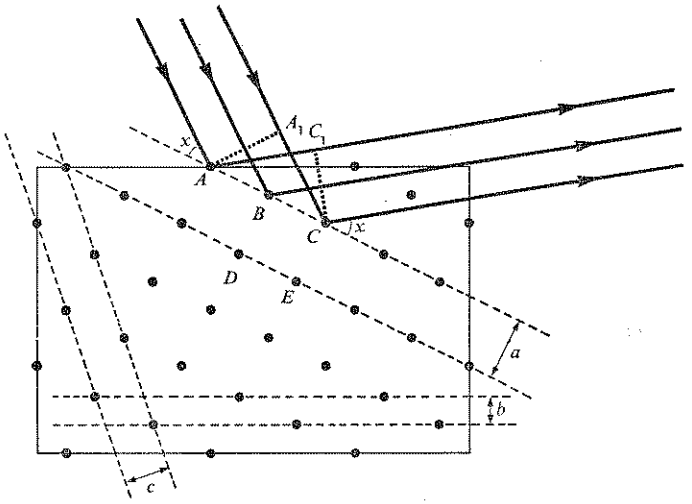
$AC_1 = A_1C$

AC is common

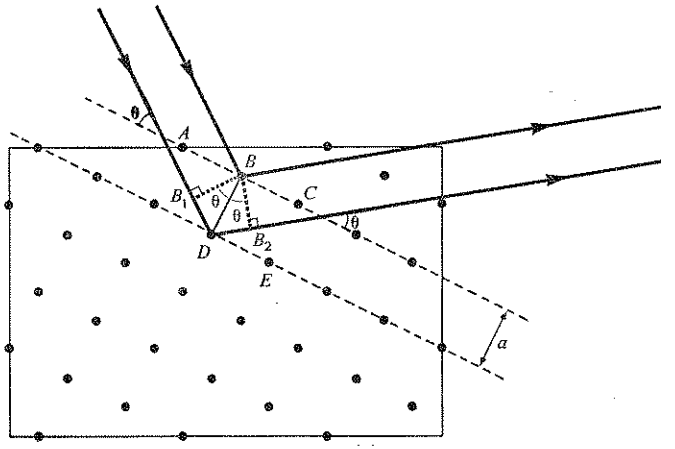
Therefore $\angle C_1CA = \angle A_1AC = 90° - x$.)

Thus for new wavefronts formed by rays scattered from crystal units in the same plane, the scattered rays and incident rays are equally inclined to the plane. This condition will hold for *any* glancing angle of incidence, x.

Some rays from the incident parallel beam, however, penetrate to lower layers of the crystal so that new wavefronts are also formed by rays scattered from units in the plane containing D, E, etc. (see Fig. 102*b*) and these



(*a*)

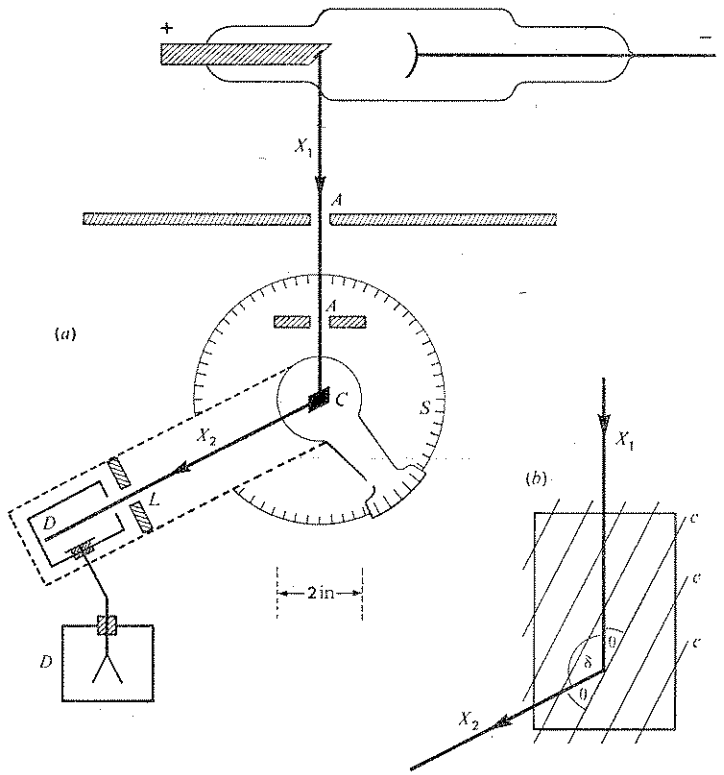


(*b*)

(*a*) Rays scattered by points in the same plane (scattered rays and incident rays are equally inclined to plane)
(*b*) Rays scattered by neighbouring planes ($2a \sin \theta = n\lambda$)

Fig. 102 X-ray diffraction by a crystal. Dotted lines show that regularly spaced units lie in sets of parallel planes

wavefronts can coincide with those from A, B, C since they are parallel. The two sets of wavefronts reinforce each other only if they are in phase



A, apertures in lead screens to define direction of incident rays; C, crystal under investigation; *c*, crystal planes; D, detector (ionisation chamber and gold leaf electroscope); L, aperture in lead screen to define direction of detector; S, scale; X_1 incident beam of X-rays; X_2 diffracted image of X-rays.
(*a*) Bragg spectrometer
(*b*) Bragg angle θ at which X-rays are diffracted by a crystal

Fig. 103 Bragg spectrometer for investigating crystal structure

when they coincide and this occurs only in certain directions θ of the incident rays: to be in phase, the path difference of the waves from different scattering points such as B and D must be an integral multiple of the wavelength,

therefore $BD + DB_2 = n\lambda$, where n is an integer.

Therefore, if BD is normal to the plane

$$BD \sin\theta + BD \sin\theta = n\lambda$$

$$\text{Hence } 2a \sin\theta = n\lambda,$$

where a is the spacing between crystal planes

This condition also holds if BD is not a normal to the planes since the paths between the incident and new wave fronts of all rays scattered by points in the plane of Band E are of the same length.

The similarity between the above proof for equal glancing angles x and that for reflection of light using Huygens' wave theory is evident. For X-rays, however, the scattering points are taken as discrete because their separation is of the same order of magnitude as the wavelength while light waves are much longer so that the separation of the points may be taken as zero by comparison, i.e. the surface from which the reflected rays originate is continuous.

It should be noted that we have been considering a true case of *diffraction* because the rays penetrate into the interior of the crystal; reflection is a purely surface phenomenon.

31 Conditions for X-ray diffraction

Thus the conditions for a diffracted image to be formed by a crystal whose spacing is a are twofold:

i Glancing angle of incidence = glancing angle of diffraction.
ii $2a \sin\theta = n\lambda$. This equation is known as the *Bragg relation.*

The glancing angle θ at which a diffracted image is obtained is called the *Bragg angle*; it is measured *with* the plane and not with the normal as is customary for light.

32 Bragg spectrometer

As we have already seen, the regularly spaced units of a crystal lie in sets of parallel planes (Fig. 102*a*). The structure of a crystal may be determined from a knowledge of the spacings *a*, *b*, *c*, etc., between the different sets of planes and the corresponding orientation of the planes relative to some axis of reference in the crystal.

One method of making these measurements is to use a Bragg spectrometer as shown in Fig. 103*a* which has many features in common with an optical spectrometer. The single crystal C to be studied is mounted on a rotatable central table of about two inches in diameter. Monochromatic X-rays of known wavelength λ are limited to a narrow beam by means of apertures in two lead screens A,A and are directed on to the crystal. The diffracted rays are received by some suitable detector D which in the original apparatus consisted of an ionisation chamber and gold leaf electroscope.

The crystal is turned by rotating the table and then the ionisation chamber is moved round, until positions for both crystal and chamber are found for which a strong diffracted image is obtained, as indicated by the response

of the gold leaf electroscope; the lead screen L with its narrow slit helps to define the direction of the diffracted beam more precisely. The Bragg angle θ is calculated from the angle δ between the diffracted and the incident rays (see Fig. 103*b* in which $\delta = 180 - 2\theta$). The spacing a between the crystal planes can then be determined using the Bragg relation $2a \sin\theta = n\lambda$; n is a small integer, probably 1, 2, or 3, and the appropriate value can usually be estimated by inspection. The direction of the corresponding crystal planes is the external bisector of the angle δ in Fig. 103*b*. The measurements are repeated for different sets of parallel planes and from these data it is possible to build up the structure of the crystal.

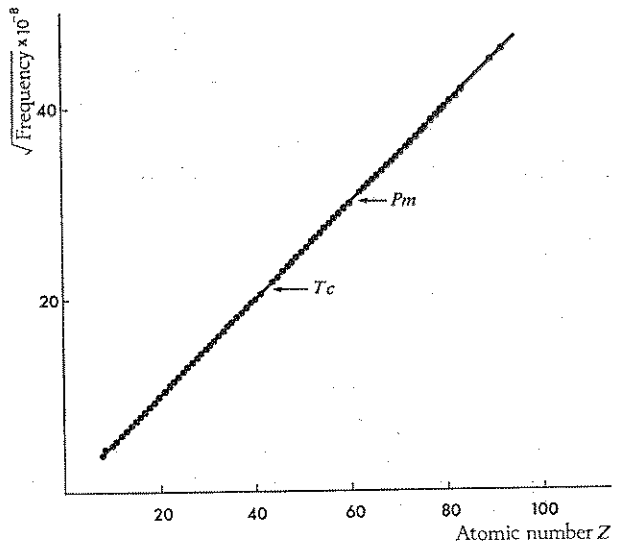
Using the above technique which was pioneered by Sir William Bragg and his son Sir Lawrence Bragg in 1913 many crystal structures have been determined, the first of which was that of rocksalt which can be seen in Fig. 82. In early experiments crystals of about one inch were used but more sensitive detecting devices now enable the method to be applied to crystals as small as 1 millimetre.

33 Moseley's law and the periodic table

We have seen how X-rays of known wavelength can be used to determine crystal structure. Equally, a crystal of known structure can be used to investigate the wavelength of X-rays. In 1913 Moseley used a Bragg spectrometer for this purpose and investigated the X-rays emitted by various elements. He used for the diffraction a crystal of potassium ferrocyanide which has a cubic structure whose spacing a could be calculated (density $= \frac{M}{Na^3}$, where M is molecular weight and N is Avogadro's number). The material under investigation was made into the target of a Coolidge type of X-ray tube.

Moseley found that the X-ray line spectra emitted by different elements are very like one another and much simpler than the corresponding visible spectra, and he deduced that X-rays originate from inside the atom, whereas the visible spectrum is governed by the more complex structure at the surface of the atom. Two clear lines in the X-ray region are emitted by all except the very light elements, and he found empirically that for the shorter wave the frequency $\nu \propto (Z-\sigma)^2$, where Z is the atomic number and σ is a small constant; this relation has become known as Moseley's law (Fig. 104).

In analysing his results, Moseley found a few anomalies in the atomic numbers that were accepted at that time. Consecutive atomic numbers had been allocated to elements when put in order of increasing atomic weights but Moseley found, for example, that the atomic number of argon



Pm (promethium) and Tc (technetium) are 'missing elements' because all their isotopes are radioactive. They can be made artificially.

Fig. 104 Moseley's Law for X-rays. Graph shows $\sqrt{\nu} \propto (Z-\sigma)$ *and hence* $\nu \propto (Z-\sigma)^2$, where σ is a small constant

(weight = 40) should be less than that of potassium (weight = 39). He also realised that certain gaps must be left in the atomic numbers, such as $Z = 43$, implying that the corresponding element could exist but had not then been discovered (it has since been made artificially and is called technetium, but all its isotopes are radioactive with half-lives which are too short for it to be found among natural ores).

Moseley drew from his observations the important conclusion that *the atomic number has a physical significance* and he identified it with the positive charge on the nucleus.

*34 Structure of molecules

We have seen that the *positions* of the diffracted images can be used to investigate the arrangement of the crystal units as a whole. It may be shown that the *intensities* of the diffracted images yield information concerning the arrangement of atoms in the crystal unit. This is the principle underlying much of the work that is at present being done on the structure of large molecules. (See Plate 11.) The molecules must first be built into crystals, such that each molecule forms a single unit of the crystal,

and this in itself is often very difficult to accomplish. The calculations involved are extremely complex but may be solved with the aid of computers, and the method has proved successful in unravelling the structure of the large organic molecules: myoglobin contained in muscles, haemoglobin in the blood and the antiseptic lysozyme present in tears, each of whose molecules contain many thousands of atoms.

CONCLUSION

35 What is light: waves or particles?

We have mentioned two different ideas concerning the nature of light and other electromagnetic radiations which at first sight appear to be incompatible: in order to explain some phenomena, such as the photo-electric effect and atomic spectra, light must be considered as being made up of particle-like units called photons, but in order to explain other phenomena, such as diffraction and interference, light must be considered to consist of waves. The apparent incompatibility of these two conceptions has been resolved by the very complicated mathematics of wave mechanics, in which certain approximations give light the characteristics of particles while other approximations give it the characteristics of waves. (Wave mechanics should not be confused with Huygens' wave theory of light in which light is considered purely as a mechanical wave motion in a hypothetical 'ether'.)

In broad terms, when the dimensions of the apparatus are very much smaller than the wavelength, then the concept of photons must be used, but when the dimensions are of the same order of magnitude as the wavelength or slightly larger, then waves give the best approximation. We can, in fact, go one further and say that when the dimensions of the apparatus are much larger than the wavelength, then geometric optics provides the best explanation.

For example, the diameter of an atom is about 1 angstrom unit, i.e. 10^{-8} centimetres, which is much smaller than the wavelength of visible light (6 000 angstrom units), so when considering the interaction between individual atoms and light, we must think in terms of photons; this aspect is used in connection with the photo-electric effect and spectra. The spacing of a typical optical diffraction grating is 2 000 angstrom units, which is comparable with the wavelength of light, so that diffraction of light must be considered in terms of waves. When considering the interaction between atoms and X-rays which have a typical wavelength of 1 angstrom unit which is therefore similar to the size of an atom, we again think in terms of waves, as for example, the diffraction of X-rays by atoms in a crystal.

The equivalence of light waves and particles proves to be just one example of an important universal concept known as *particle-wave duality* which is discussed more fully in Chapter 15.

Problems on Chapter Twelve

Magnetism

1. Distinguish between diamagnetism, paramagnetism, and ferromagnetism. How can these properties be explained in terms of the structure and arrangement of the atoms?

Photo-electric effect

2. Describe briefly and explain one experiment to demonstrate the photo-electric effect.

Assuming monochromatic light to be used, discuss the effect on the observed phenomena of changing the wavelength. L specimen I–11 (part)

3. Discuss the emission of electrons when light falls on a photo-sensitive surface in a vacuum. How has this phenomenon modified views on the nature of light?

Describe a form of photo-cell suitable for measuring illumination. L W63 I–11

4. What is photo-electric emission and in what circumstances can the effect be observed?

What does this phenomenon contribute towards the understanding of the nature of light?

Describe how a photo-electric device may be calibrated for the measurement of relative intensities, and how it may then be used to investigate how the light emission from a lamp varies with direction. N 61 II–7

5. Describe the structure of an illumination meter of either the visual type or the photo-electric type. How could such a meter be calibrated if a standard lamp were available? L 65 I–11 (part)

6. (*a*) Describe briefly the effect of varying (i) the intensity, (ii) the frequency of light falling on a photo-sensitive surface. (*b*) Describe a photo-electric meter for measuring illumination. L W65 I–10

7. Light of wavelength $4{\cdot}08 \times 10^{-5}$ cm is found to liberate photons with energy of $1{\cdot}97 \times 10^{-12}$ ergs from a certain metal. The longest wavelength limit beyond which no photo-emission occurs for this metal is $6{\cdot}90 \times 10^{-5}$ cm. Taking the velocity of light as $3{\cdot}00 \times 10^{10}$ cm sec^{-1}, deduce a value for Planck's constant h. L 62 I–11 (part)

8. When light is incident on a metal plate electrons are emitted only

when the frequency of the light exceeds a certain value. How has this been explained?

The maximum kinetic energy of the electrons emitted from a metallic surface is $1{\cdot}6 \times 10^{-12}$ erg, when the frequency of the incident radiation is $7{\cdot}5 \times 10^{14}$ c.p.s. Calculate the minimum frequency of radiation for which electrons will be emitted. Assume that Planck's constant $= 6{\cdot}6 \times 10^{-27}$ erg-sec. N 65 II–5

9. The light energy received per unit area at a distance of 1 metre from a source of 1 candela is 1·5 erg sec^{-1} cm^{-2}. How many quanta are received per square cm per second if the light is a sodium source emitting at $5{\cdot}9 \times 10^{-5}$ cm? (Take velocity of light as $3{\cdot}0 \times 10^{10}$ cm sec^{-1} and Planck's constant, h, as $6{\cdot}6 \times 10^{-27}$ erg-sec.)

10. The eye can just see a sodium source of 10^{-8} candela at a distance of 1 metre. How many quanta must enter the eye per second in order to be observable? (Use data from Question 9 and assume the diameter of the eye to be 3 millimetres.)

11. When the sodium source of Question 9 shines on a sodium surface of area 1 sq. cm placed 1 metre away at right-angles to the rays the light is completely absorbed and gives rise to a photo-electric current of $2{\cdot}52 \times 10^{-9}$ amp. Find the probability of a photon releasing an electron. (*sometimes called the photo-electric yield*). (Use data of Question 9; electronic charge $= 1{\cdot}6 \times 10^{-19}$ coulomb.)

12. Give an account of the photo-electric effect and describe one practical application of it. State the factors that determine (*a*) the number of electrons emitted per unit area of the irradiated surface, and (*b*) the energy with which these electrons leave the surface. Discuss these results briefly in terms of the quantum theory of radiation.

Taking the work function of caesium to be 1·9 electronvolts and the electronic charge to be $1{\cdot}6 \times 10^{-19}$ coulomb, Planck's constant, h, to be $6{\cdot}5 \times 10^{-27}$ erg-sec, and the velocity of light in vacuo to be $3{\cdot}0 \times 10^{10}$ cm sec^{-1} calculate the maximum kinetic energy with which an electron can leave a caesium surface exposed to light of wavelength $5{\cdot}6 \times 10^{-5}$ cm. O Sp 64–13

Spectra

13. Explain what you mean by the term *electromagnetic spectrum*. Show with the aid of a diagram with wavelengths indicated, how this spectrum is commonly divided into various regions. Indicate briefly the physical processes involved in the production of the radiations of the different regions. N Sp 62–8

14. Discuss the facts that led to the Rutherford-Bohr model of the atom and explain how it has contributed to the understanding of spectral lines.

15. What are the chief characteristics of a line spectrum? Explain how line spectra are used in the analysis for the identification of elements.

The energies associated with the six lowest energy levels of the hydrogen atom, measured in electronvolts, are as follows: −13·58, −3·39, −1·51, −0·85, −0·54, −0·38. Work out the wavelengths of lines associated with transitions to the −3·39 eV level from each of the higher levels. Show that other transitions that can occur give rise to lines that are either in the ultra-violet or in the infra-red regions of the spectrum. (Take 1 eV to be $1{\cdot}6 \times 10^{-12}$ erg, Planck's constant h to be $6{\cdot}5 \times 10^{-27}$ erg-sec and c, the velocity of light in vacuo, to be $3{\cdot}0 \times 10^{10}$ cm sec^{-1}.) O 64 II–14

X-rays

16. Describe and explain the structure and mode of operation of a modern form of X-ray tube. L 63A II–6 (part)

17. How are X-rays generated? Describe the construction and operation of a modern form of X-ray tube, and outline the properties of the rays. S 63 II–11

18. Describe the equipment required for the production of (*a*) cathode rays, (*b*) X-rays. Compare and contrast the properties of cathode rays and X-rays. L 65A II–6

19. Describe the modern hot cathode X-ray tube, and give a diagram of a circuit suitable for its operation.

Discuss briefly the energy conversion that takes place in the tube.

If the p.d. across the tube is 1 500 volt and the current 10^{-3} amp, find (*a*) the number of electrons crossing the tube per second, (*b*) the kinetic energy gained by an electron traversing the tube without collisions. (Take electronic charge to be $1{\cdot}6 \times 10^{-19}$ coulomb.) O 63 I–12

20. Give an account of the properties of X-rays and describe with a diagram a modern form of X-ray tube.

An X-ray tube works at a potential difference of 100 000 volts. Only 0·1 per cent of the energy of the cathode rays is converted into X-radiation and heat is generated in the target (anti-cathode) at the rate of 120 cal. per sec. What current does the tube pass and what is the energy and velocity of an electron when it reaches the target? (Neglect relativistic effects. Electronic charge $= 1{\cdot}6 \times 10^{-20}$ e.m.u.; electronic mass $= 9{\cdot}1 \times 10^{-28}$ g; $4{\cdot}2 \times 10^{7}$ erg = 1 cal.; 1 volt $= 10^{8}$ e.m.u.) S 61 II–10

21. Describe with the aid of a labelled diagram the main features of the structure of a modern form of X-ray tube. Give an account of the electrical supplies required for such a tube. (Do not describe how these supplies are produced.)

Outline the energy changes occurring in the tube when it is in operation.

Compare and contrast the properties of X-rays and visible light.

N 63 II–7

22. An X-ray tube operating at 20 kV emits a continuous spectrum with a short wavelength limit of $6{\cdot}2 \times 10^{-9}$ cm. Calculate Planck's constant h. (Electronic charge $= 1{\cdot}6 \times 10^{-19}$ coulomb; velocity of light in vacuo $= 3{\cdot}0 \times 10^{10}$ cm sec^{-1}).

23. The electron beam of an X-ray tube delivers 1 kW of power to the copper anode over an area of 10 mm by 1 mm. The anode is 1 millimetre thick and is cooled by a water jacket supplied directly from the water main at 15°C. If the water outflow temperature is 30°C, calculate the rate of flow of cooling water you would require and the hot surface temperature of the anode in these conditions neglecting the sideways flow of heat. (1 cal $= 4{\cdot}18$ joules, conductivity of copper $= 0{\cdot}92$ cal cm^{-1} sec^{-1} deg C^{-1}.)

N Sp 62–5 (part)

24. The crystal spacing of rocksalt is $2{\cdot}82 \times 10^{-8}$ cm. For the first order diffracted image of some monochromatic X-rays the Bragg angle is 15° 53′. Calculate the wavelength of the X-rays and the Bragg angle for the second order image. Calculate also the longest wavelength that can be analysed by this crystal.

General

25. Compare and contrast the properties of the *proton*, *neutron*, and *electron*. Explain the rôle played by each of these particles in the structure of the atom. How is your account of the arrangement of the electrons in the atom supported by experimental evidence? L 65 II–12 (part)

26. In the eighteenth century a corpuscular theory of light was dominant; in the nineteenth century this theory was discarded in favour of the undulatory theory; now, in the twentieth century it is believed that light has both particle and wave characteristics. Discuss the reasons for these changes of opinion. N Sp. 60–4

Part Four

Further Topics