TOPIC 13
The structure of the atom

13.1 Overview

13.1.1 Module 8: From the Universe to the Atom

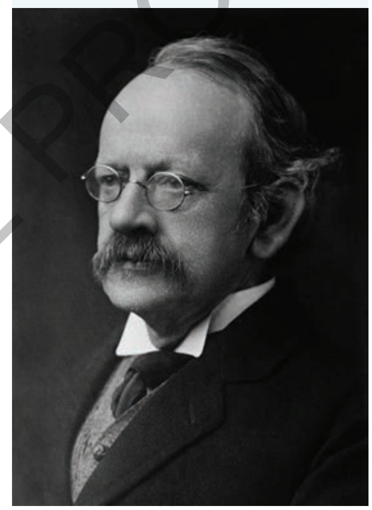
Structure of the atom

Inquiry question: How is it known that atoms are made up of protons, neutrons and electrons?

Students:

- investigate, assess and model the experimental evidence supporting the existence and properties of the electron, including:
  - early experiments examining the nature of cathode rays
  - Thomson's charge-to-mass experiment
  - Millikan's oil drop experiment (ACSPH026)
- investigate, assess and model the experimental evidence supporting the nuclear model of the atom, including:
  - the Geiger–Marsden experiment
  - Rutherford's atomic model
  - Chadwick's discovery of the neutron (ACSPH026)

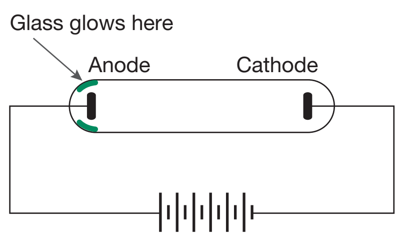
FIGURE 13.1 The famous physicist J.J. Thomson (1856–1940) was celebrated for his experiments with the electron.



13.2 Cathode rays and the electron

13.2.1 The discovery of cathode rays

FIGURE 13.2 Production of cathode rays in a discharge tube, as used by Plucker



In the early part of the nineteenth century, the discovery of electricity had a profound effect on the study of science. By the 1850s, much was known about which solids and liquids were electric conductors or insulators, and it was thought that gases were electric insulators.

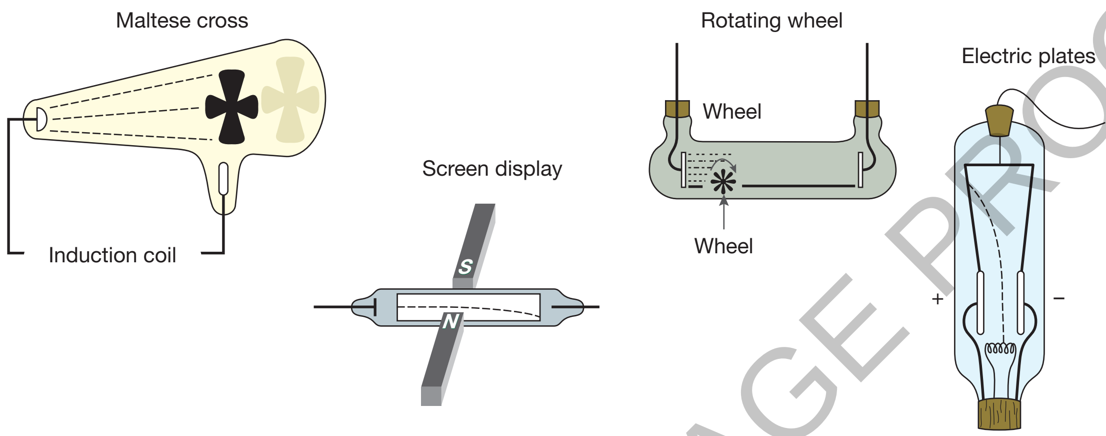
The development of a vacuum, using pumps to remove the air from glass tubes, was also being actively researched at this time. As improved vacuum pumps were developed, scientists were able to experiment with gases at very low pressures. In 1855, a German physicist, Heinrich Geissler (1814–1879), refined a vacuum pump so that it could be made to evacuate a glass tube to within 0.01 per cent of normal air pressure. Geissler's friend, Julius Plucker (1801–1868), took these tubes and sealed a metal plate, called an electrode, to each end of the tube. The electrodes made electrical connections through the glass and were sealed to maintain the partial vacuum in the tube. These were then connected to a high-voltage source, as illustrated in figure 13.2. To their surprise, the evacuated tube actually conducted an electric current. What puzzled them more was the fact that the glass at the positive end, or **anode**, of the vacuum tube glowed with a pale green light. What type of invisible 'ray' caused this glow or **fluorescence**?

Whatever it was must have originated at the negative electrode, or **cathode**, of the vacuum tube. Another physicist, Eugene Goldstein (1850–1930), who was studying these same effects, named the rays that caused the glow 'cathode rays', and the tubes became known as **cathode ray tubes** or **discharge tubes** (see figure 13.3). Early experimenters used these tubes to investigate all of the properties of cathode rays and

X-rays. Some modified the cathode ray tube to include a rectangular metal plate covered in zinc sulphide inside the tube. This plate had a horizontal slit cut into the end nearest the cathode and the plate was slightly bent so that the cathode rays formed a horizontal beam. When the cathode rays struck this material it appeared fluorescent and showed the path of the rays through the tube.

Cathode ray tubes have been refined and developed and are now used in television sets, computers and many other applications.

FIGURE 13.3 A variety of early discharge tubes used in experiments



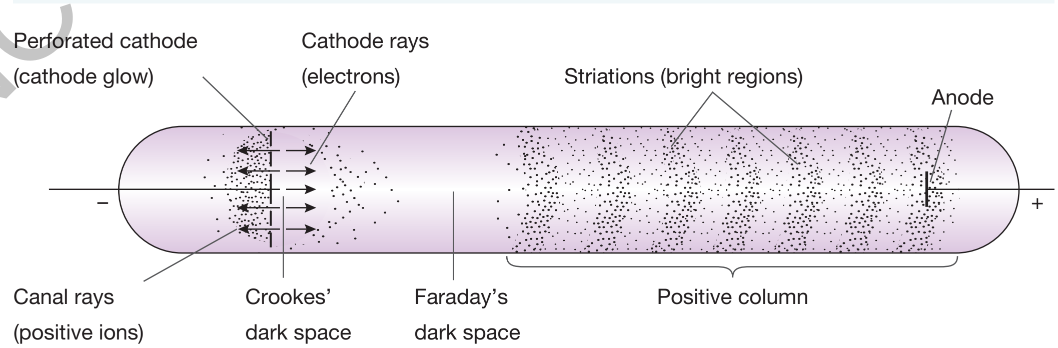
13.2.2 Discharge tubes

Discharge tubes evacuated to different air pressures were found to produce different effects.

For example, in practical activity 13.1, an induction coil acts as a step-up transformer, delivering a high voltage across the set of discharge tubes. At low pressures, electrons can accelerate to faster speeds before colliding with gas particles. Initially, a current will flow even though nothing can be seen. The first effect that can be observed is a steady luminous discharge known as a 'glow discharge'. As the pressure is lowered further, a number of colourful effects can be seen.

At first, most of the tube is occupied by a bright luminous region called a 'positive column' which appears to start from the anode and is broken up into a series of bands or striations (see figure 13.4). Near the anode, a weaker glow can be seen. The striations are separated by 'dark spaces'. These discharges and spaces are named after some of the scientists who examined them, for example, 'Ashton's dark space', 'Crookes' dark space' and 'Faraday's dark space'. The colours of the discharge depend on the gas used. In low pressure air, the positive column is a brilliant pink and the negative glow is deep blue.

FIGURE 13.4 Some of the effects observed in discharge tubes



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Everyday uses of discharge tubes

Neon signs colour the night in every city street. They are long tubes with most of the air removed. A small amount of gas is introduced which, when excited by a high potential, glows with a characteristic colour. For example, when the added gas is neon, the kinetic energy of the electrons is sufficient to ionise the gas around the cathode causing the emission of a reddish light.

Fluorescent tubes in the home contain mercury vapour at low pressure. The light produced is in the ultraviolet region of the electromagnetic spectrum. To produce visible light, a thin coating of a powder is spread on the inside surface of the tube. The ultraviolet radiation causes this coating to fluoresce with the familiar bright white light.

FIGURE 13.5 Discharge tubes are used in the neon lights that are often a feature of streetscapes and venue advertising at night.

13.2.3 The effect of electric fields on cathode rays

You are familiar with three types of fields: gravitational, electric and magnetic. An electric field exists in any region where an electric charge experiences a force. There are two types of charge — positive and negative. We define the direction of the electric field as the direction in which a positive charge will experience a force when placed in an electric field.

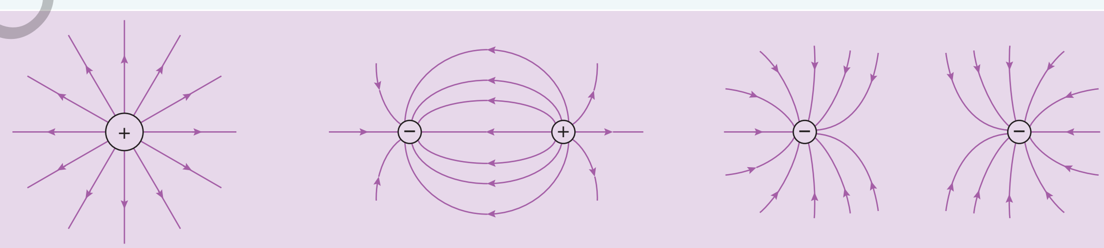
This definition of an electric field allows us to describe the fields around a charge (see figure 13.6). Using Faraday's 'lines of force', we see that these lines radiate from a point at the centre of the charge. For a positive charge, lines of force leave the centre of the charge and radiate in all directions from it. For a negative charge, the lines are directed radially into the centre of the charge.

If a positive charge is placed near another positive charge, it will experience a force of repulsion; that is, a force which acts in the direction of the arrow.

A number of rules apply to the interpretation of these lines of force diagrams (see figure 13.6).

- Field lines begin on positive charges and end on negative charges.
- Field lines never cross.
- Field lines that are close together represent strong fields.
- Field lines that are well separated represent weak fields.
- A positive charge placed in the field will experience a force in the direction of the arrow.
- A negative charge placed in the field will experience a force in the direction opposite to the arrow.

FIGURE 13.6 Electric fields around charges



(a) Electric field around a single positive charge (b) Opposite charges (c) Like charges

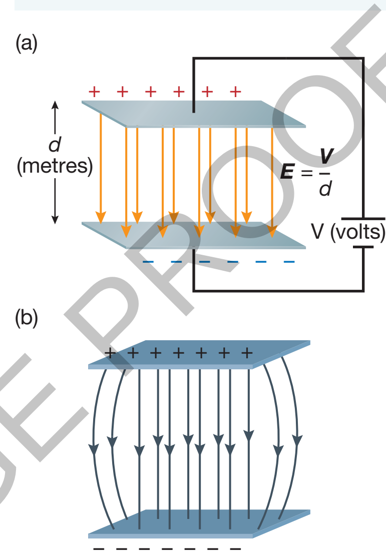
Uniform electric fields

A uniform electric field can be made by placing charges on two parallel plates which are separated by a small distance compared with their length. These electric fields are very useful in physics and were used by prominent scientists such as Robert Millikan and J. J. Thomson when investigating the properties of small charged particles.

Consider the electric field between two plates that are separated by d metres, as shown in figure 13.7(a).

The magnitude, or intensity, of an electric field is determined by finding the force acting on a unit charge placed at that point. The symbol for electric field is $\boldsymbol{E}$.

FIGURE 13.7 (a) Electric field (E) between two parallel plates. (b) The electric field is uniform except at the edges of the plates where it bulges slightly.



$$\boldsymbol{E} = \frac{\boldsymbol{F}}{q}$$

where

$\boldsymbol{E}$ = electric field intensity (in newtons per coulomb)

$\boldsymbol{F}$ = electric force (in newtons, N)

q = electric charge (in coulombs, C).

When the potential difference, or voltage, is applied to the plates, a uniform electric field is produced. The strength of this field is the same at all points between the plates, except near the edges where it 'bulges' slightly (see figure 13.7(b)).

The magnitude of the electric field, $\boldsymbol{E}$, is given by:

$$E = \frac{V}{d}$$

where

V = potential difference, in volts.

This can be derived by recalling that potential difference is the change in potential energy per unit charge moving from one point to the other. The amount of energy or work is given by:

$$W = qV.$$

Also, the work done by a force is the product of the force and the distance moved, d. In this case, $F = qE$. Hence, the amount of work is given by:

$$W = Fd = qEd$$

It follows that: $V = Ed$ or $E = \frac{V}{d}$.

Remember that *work done is equal to the gain in energy*.

A small positive charge released next to the positive plate will experience a force that will accelerate the charge. The charge will increase its kinetic energy.

$$W = qV = \frac{1}{2}mv^2$$

This shows that the amount of work done depends only on the potential difference and the charge, and is the same for both uniform and non-uniform electric fields.

13.2 SAMPLE PROBLEM 1

ELECTRIC FIELD STRENGTH

What is the electric field strength between two parallel plates separated by 5.0 mm, if a potential difference of 48 volts is applied across them?

SOLUTION:

$$\begin{aligned} V &= 48 \text{ volts} \\ d &= 5.0 \text{ mm} \\ &= 5.0 \times 10^{-3} \text{ m} \\ E &= \frac{V}{d} \\ &= \frac{48}{5.0 \times 10^{-3}} \\ &= 9600 \text{ V m}^{-1} \text{ or N C}^{-1} \end{aligned}$$

13.2 SAMPLE PROBLEM 2

MOVING CHARGE THROUGH A POTENTIAL DIFFERENCE

How much work is done moving a charge of 3.6 μC through a potential difference of 15 volts?

SOLUTION:

$$\begin{aligned} q &= 3.6 \times 10^{-6} \text{ C} \\ V &= 15 \text{ volts} \\ W &= qv \\ &= 3.6 \times 10^{-6} \times 15 \\ &= 5.4 \times 10^{-5} \text{ J} \end{aligned}$$

13.2 SAMPLE PROBLEM 3

VELOCITY OF A CHARGE BETWEEN PLATES

Two parallel plates are separated by a distance of 5.0 mm. A potential difference of 200 volts is connected across them. A small object with a mass of 1.8×10^{-12} kg is given a positive charge of 12 μC. It is released from rest near the positive plate. Calculate the velocity gained as it moves from the positive plate to the negative plate.

SOLUTION:

$$\begin{aligned} d &= 5.0 \times 10^{-3} \text{ m} \\ V &= 200 \text{ V} \\ q &= 1.2 \times 10^{-5} \text{ C} \\ m &= 1.8 \times 10^{-12} \text{ Kg} \\ qV &= \frac{1}{2} mv^2 \\ v^2 &= \frac{2\left(1.2 \times 10^{-5} \times 2.00 \times 10^2\right)}{1.8 \times 10^{-12}} \\ v &= 5.2 \times 10^4 \text{m s}^{-1} \end{aligned}$$

13.2 Exercise 1

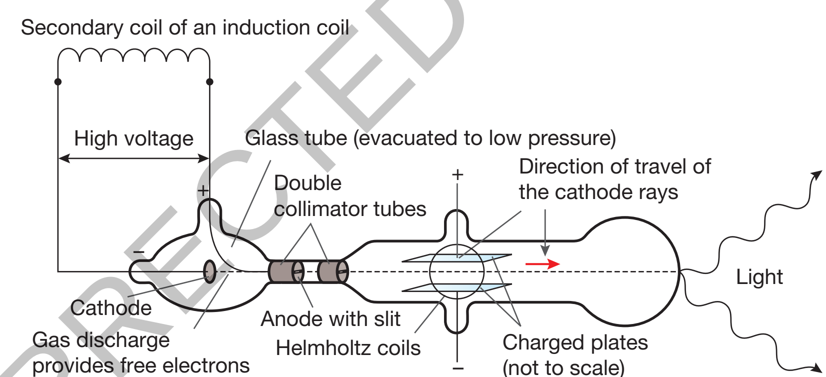
1 A research scientist wishes to make a uniform electric field of strength 200 N C^{-1} between two parallel plates separated by 12.5 cm.
(a) State the electric field strength in V m^{-1}.
(b) Calculate the potential difference applied to the plates to make an electric field strength as specified.
(c) A positive test charge $q = 2.0 \times 10^{-4}$ C is placed in between the plates. Determine the size and direction (towards the positive plate or towards the negative plate) of the electric force acting on the test charge.
(d) If the plates were moved further apart, what effect, if any, would this have on the size of the electric force acting on the test charge?

13.2.4 The work of J.J. Thomson — determining the charge/mass ratio for cathode rays

J. J. Thomson

The work of English physicist Joseph John Thomson (1856–1940) centred around cathode rays. By incorporating charged plates inside the cathode ray tube, Thomson was able to verify an earlier hypothesis by Crookes that cathode rays would be deflected by electric fields (see figure 13.8). In Thomson'sexperiment, the cathode rays passed between parallel plates connected to a battery. He observed that the direction of the rays moved towards the positively charged plate, showing that the rays behaved as negative charges.

FIGURE 13.8 The apparatus for J. J. Thomson's experiments with cathode rays



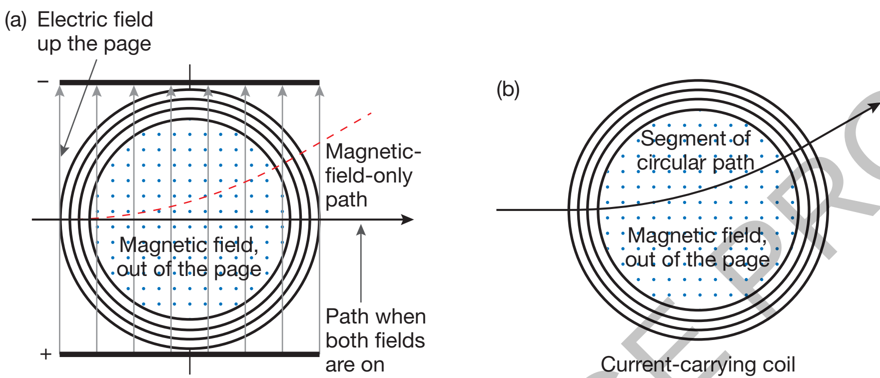
J. J. Thomson was an intuitive and brilliant experimentalist. Following on from his experiment showing that cathode rays were deflected by electric fields, he succeeded in measuring the charge-to-mass ratio of the cathode ray particles, called electrons. Thomson built a cathode ray tube with charged parallel plates (called capacitor plates) to provide a uniform electric field and a source of uniform magnetic field. Using this apparatus, he investigated the effect of cathode rays passing through both fields (see figure 13.9). The fields were oriented at right angles to each other and this had the effect of producing forces on the cathode rays that directly opposed each other (see the 'Physics fact' below).

Thomson's experiment involved two stages:

1. varying the magnetic field and electric fields until their opposing forces cancelled, leaving the cathode rays undeflected. This effect is shown in figure 13.9(a). By equating the magnetic and electric force equations, Thomson was able to determine the velocity of the cathode-ray particles.
2. applying the same strength magnetic field (alone) and determining the radius of the circle path travelled by the charged particles in the magnetic field (see figure 13.9(b)).

Thomson combined the results and obtained the magnitude of the charge-to-mass ratio for the charged particles that constituted cathode rays.

FIGURE 13.9 (a) A beam of negatively charged particles left undeflected by the combination of a magnetic field out of the page, and an electric field up the page (b) A negatively charged particle deflected by a magnetic field out of the page. The mechanics of circular motion describes the path, with the centripetal force provided by the magnetic force acting on the particle.



PHYSICS FACT

When charged particles enter an electric field they follow a trajectory under the influence of an electric force.

Similarly, when a charged particle enters a magnetic field, it experiences a magnetic force. The direction of this force is given by the right-hand palm rule.

We can combine these two effects by arranging the electric field, magnetic field and the velocity of the particle at right angles to each other.

For example, by adjusting the strengths of the electric and magnetic fields, their effects on the motion of a charged particle can cancel each other out. The particles can then travel along a straight path.

In figure 13.8, there are two sets of electric fields. The first accelerates the electrons through a set of collimators to produce a narrow beam. This beam then passes through a combination of electric and magnetic fields that can be adjusted.

FIGURE 13.10

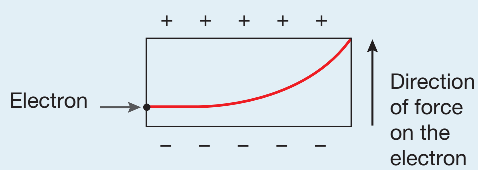


FIGURE 13.11

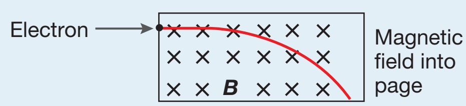
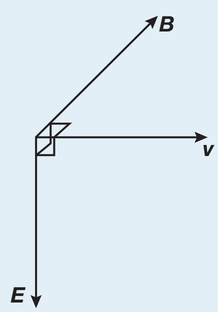


FIGURE 13.12

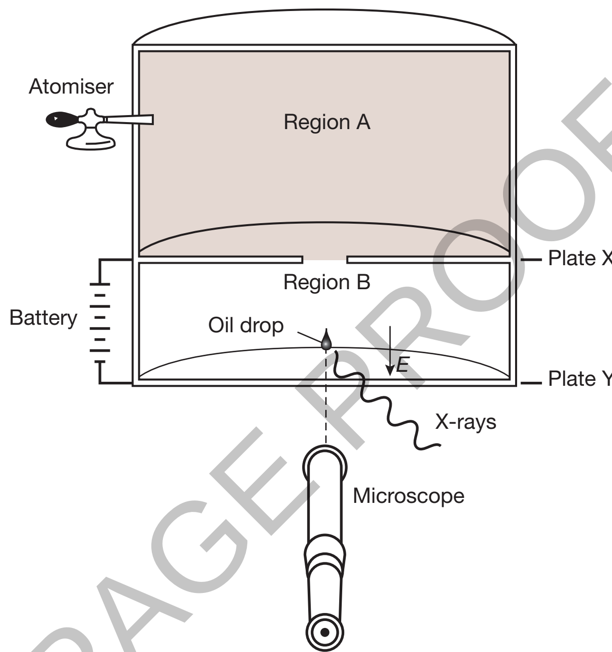


13.2.5 The work of Millikan — determining the quantum of charge — the charge on an electron

In 1909, American physicist, Robert A. Millikan, was able to use the uniform electric field created between two parallel plates to investigate the properties of a charge. His set-up (see figure 13.13) involved an atomiser that sprayed a fine mist of oil drops into his apparatus (region A).

Some drops drifted into region B and came under the influence of the electric field, E. As the oil drops entered this region they were momentarily exposed to a beam of X-rays, resulting in some of the oil drops becoming charged. The gravitational field of the Earth exerts a force directed vertically down (weight) that can be counteracted by an electric field produced between parallel plates by a source of variable voltage. The spaces between the plates could be viewed through a microscope. By careful adjustments of the voltage it was possible for one drop to be held stationary, or made to travel with uniform velocity. That is, the forces acting on the drop were balanced.

FIGURE 13.13 Apparatus for Millikan's oil drop experiment



$$\text{Weight force (down)} = F_g = mg$$
$$\text{Electric force (up)} = F_E = Eq$$

For this drop to be suspended between plates, $F_g = F_E$.

Having suspended an oil drop, Millikan could then determine the charge on that particular oil drop by solving for q; that is, $q = \frac{mg}{E}$.

Millikan needed to determine the mass of the oil drop. His approach was to measure the terminal velocity of the oil drop when the electric field was turned off and it fell under the force of gravity alone. By using equations from fluid mechanics, he could calculate the radius of the oil drop. By using an oil with a known density, he was able to determine the mass of the oil drop.

Millikan's remarkable findings, for which he won a Nobel Prize in 1923, showed that the charge on an oil drop was not of just any arbitrary value. Instead, the charge always occurred in 'packets' or multiples of some smallest value. This value was calculated to be 1.6×10^{-19} C and was called the 'elementary charge', the charge found on an electron.

13.2 SAMPLE PROBLEM 4

FIELD STRENGTH AND THE CHARGE ON AN OIL DROP

An oil drop of mass 6.8×10^{-6} g is suspended between two parallel plates which are separated by a distance of 3.5 mm, as shown in figure 10.12.

(a) What is the electric field strength between the plates?
(b) What is the charge that must exist on the oil drop?
(c) How many excess electrons must be present on the oil drop?

SOLUTION:

(a) Using the equation $E = \dfrac{V}{d}$:

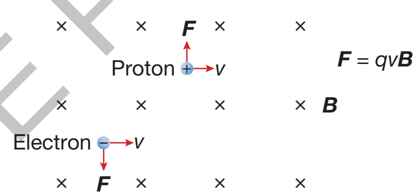
$$E = \frac{110}{3.5 \times 10^{-3}}$$
$$= 3.1 \times 10^{4}\ \text{Vm}^{-1}\text{down.}$$

13.2.6 The effect of magnetic fields on cathode rays

Magnetic fields exert forces on electric currents; that is, on moving charged particles. If a particle with charge q is moving with velocity v, perpendicularly to a magnetic field of strength B, the particle will experience a magnetic force F, given by $F = qvB$.

The direction of the force is given by the right-hand rule. (If the particle has a positive charge, the direction of the conventional current is that of the velocity; if the particle has a negative charge, the direction of the conventional current is opposite to that of the velocity.) This is illustrated in figure 13.14 for an electron (negative charge) and a proton (positive charge).

FIGURE 13.14 Forces on an electron and a proton moving perpendicularly to a magnetic field



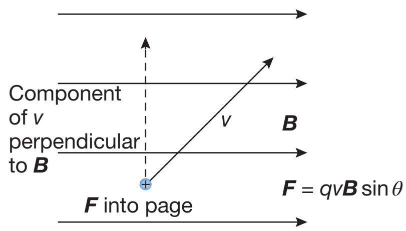
If the velocity is at an angle θ to the magnetic field, the force is given by

$$F = qvB \sin\theta.$$

To find the direction of the force, use the component of the velocity perpendicular to the magnetic field and the right-hand rule. This is illustrated in figure 13.15 where the direction of the force is into the page.

If the charged particle is moving parallel to the magnetic field, $\theta = 0$, and therefore $F = 0$.

FIGURE 13.15 Force on a charged particle moving at an angle, θ to a magnetic field



13.2 SAMPLE PROBLEM 5

EFFECTS OF MAGNETIC FIELDS ON ELECTRONS

An electron of charge -1.6×10^{-19} C is projected into a region where a magnetic field exists, as shown in the diagram. If the velocity of the electron is $2.5 \times 10^{4}\ \text{m s}^{-1}$, determine:

(a) the force on the electron at the instant it enters the magnetic field

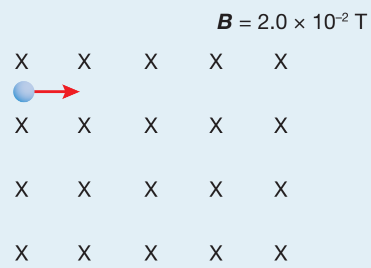
(b) the shape of the path that the electron follows.

SOLUTION:

(a) $F = qvB \sin\theta$
$= 2.0 \times 10^{-2} \times 1.6 \times 10^{-19} \times 2.5 \times 10^{4}$
$= 8.0 \times 10^{-17}$ N downwards.

(b) The path that the electron follows will be circular. This is because the magnetic force is always acting perpendicular to the velocity of the electron.

FIGURE 13.16

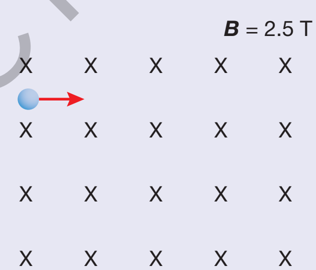


13.2 Exercise 2

1 A pair of horizontal parallel plates (45 mm separation) is arranged such that the potential difference applied across the plates is 56 V. An oil drop is suspended between the plates in equilibrium.
 (a) Which of the plates, top or bottom, would be positive?
 The oil drop is known to have excess electrons equal to 5.0×10^{8}.
 (b) Determine the mass of the oil drop.

2 A horizontal beam of electrons is fired into a region containing a uniform magnetic field of 2.5 T directed vertically downwards.

FIGURE 13.17



 (a) The electrons in the beam followed a circular path. Explain why.
 (b) An analysis of the path taken by the electrons determined the force acting on each of them to be 2.0×10^{-15} N. Use this information to calculate the velocity of the electrons.

13.2.7 Cathode rays — waves or particles

In 1875, twenty years after their discovery, William Crookes (1832–1919) designed a number of tubes to study cathode rays (some of these are shown in figure 13.3). He found that the cathode rays did not penetrate metals and travelled in straight lines. It was initially thought that the rays may be an electromagnetic wave because of the similarity in their behaviour to light. This was discounted when Crookes discovered that the cathode rays were deflected by magnetic fields, an effect which did not occur with light.

In a paper read to the Paris Academy of Science in 1885, Jean Perrin (1870–1942) described the two main hypotheses concerning the nature of cathode rays:

Some physicists think, with Goldstein, Hertz and Lenard, that this phenomenon is like light of very short wavelength. Others think, with Crookes and J. J. Thomson, that these rays are formed by matter which is negatively charged and moving with great velocity, and on this hypothesis their mechanical properties, as well as the manner in which they curve in a magnetic field, are readily explicable.

The way that physicists set out to understand the nature of cathode rays shows how the scientific method is used to solve problems. That is, observations from experiments are interpreted and a hypothesis developed to explain what is thought to be happening. Opposing models may arise, with supporters of each side arguing strongly for their belief. The argument may eventually be resolved either by improved experiments or with greater understanding of the phenomenon.

In this case, the debate about whether cathode rays were electromagnetic waves or streams of charged particles remained unsolved until 1897, when J. J. Thomson showed beyond doubt that the rays were streams of negatively charged particles, which we now call electrons. Why was the debate so prolonged? The problem was the apparently inconsistent behaviour of rays. For example, the following observations from cathode ray experiments fitted the wave model:

- they travelled in straight lines
- if an opaque object was placed in their path, a shadow of that object appeared
- they could pass through thin metal foils without damaging them.

The following observations fitted the particle model:

- the rays left the cathode at right angles to the surface
- they were obviously deflected by magnetic fields
- they did not appear to be deflected by electric fields
- small paddlewheels turned when placed in the path of the rays
- they travelled considerably more slowly than light.

The main restriction for the charged particle theory was the absence of deflection in electric fields. However, Thomson showed that this was due to the rays themselves. He stated:

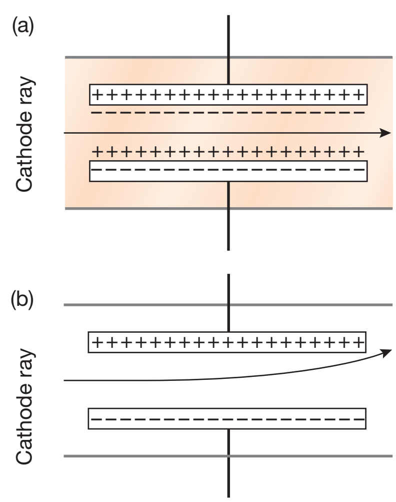
'. . . on repeating the experiment I first got the same result, but subsequent experiments showed that the absence of deflection is due to the conductivity conferred on the rarefied gas by the cathode rays. On measuring this conductivity . . . it was found to decrease very rapidly with the exhaustion of the gas . . . at very high exhaustions there might be a chance of detecting the deflection of cathode rays by an electrostatic force.'

Within the tube, the cathode rays ionised the gas. The ions were attracted to the plate with the opposite charge and the line-up of ions effectively neutralised the charge on the plate, allowing the cathode rays to pass by unaffected.

After evacuating the chamber, Thomson observed deflection and that the particles were always deflected towards the positive plate, which confirmed that they were negatively charged particles. The deflection of cathode rays in tubes of different gas pressure is shown in figure 13.18.

The ability of cathode rays to penetrate thin metal foils was still unexplained. The answer lay, not simply with the properties of cathode rays, but with the model of the atom. If the atom was not a solid object, but much more open, it might be possible for very small particles to pass through thin foil. Although not considered at this time, Ernest Rutherford (1871–1937) would use a similar approach to change the model of the atom.

FIGURE 13.18 The path of cathode rays (a) at high gas pressure and (b) at low gas pressure



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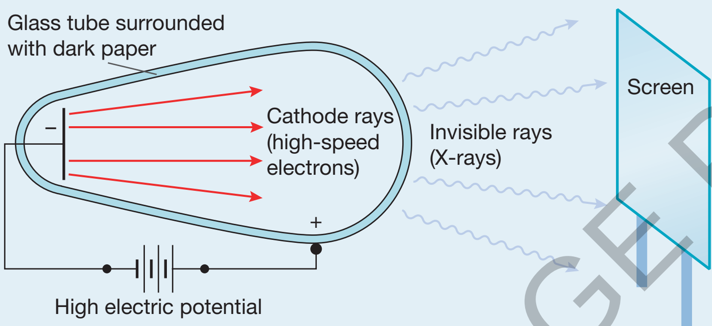
X-rays: discovery and application

In 1895, a type of radiation was discovered by Wilhelm Röntgen (1845–1923) while he was experimenting with cathode rays. He found that, in a dark room, a screen covered with a sensitive fluorescent material (barium platino-cyanide) glowed when it was placed near the end of a cathode ray tube (see figure 13.19).

FIGURE 13.19 Röntgen's apparatus



Since cathode rays could not pass through the glass at the end of the tube, he deduced that this fluorescence must be due to a new form of radiation. He called this radiation 'X-rays' as their properties were not known. Later research showed that X-rays were produced when high-speed electrons interacted with matter, such as the glass in the cathode ray tube.

X-rays were later found to be electromagnetic waves, similar to light but with a much smaller wavelength.

Among the many characteristics that make X-rays so useful are the fact that they can:

- penetrate many substances
- expose photographic film
- cause certain substances to fluoresce
- be reflected and refracted.

The most common use of X-rays is in the field of medicine, for diagnosing illness or injury as well as treating illnesses such as cancer. X-ray machines are used widely — to check luggage at airports, analyse the welding of metal parts in an aircraft wing, and look at things that we otherwise could not see.

FIGURE 13.20 X-ray of a normal knee joint (human).

13.3 The development of the classical model of the atom

13.3.1 Development of the Thomson 'plum pudding model'

TABLE 13.1 A timeline of modern physics

Year	Event
1864	James Clerk Maxwell develops the mathematical theory of electromagnetism.
1875	Sir William Crookes observes cathode rays.
1880s	Michelson–Morley experiments
1885	Heinrich Hertz produces electromagnetic waves artificially.
1888	Heinrich Hertz discovers the photoelectric effect.
1895	Wilhelm Roentgen discovers X-rays.
1896	Henri Becquerel discovers radioactivity.
1897	J J Thomson discovers the electron.
1899	Max Planck describes energy 'quanta'.
1905	Albert Einstein explains the photoelectric effect and publishes the Special Theory of Relativity.
1911	Ernest Rutherford proposes the 'solar system' model of the atom.
1912	Robert Millikan determines the electric charge on the electron.
1913	Niels Bohr proposes the quantum model of the atom.
1914	James Franck and Gustav Hertz experimentally demonstrate the existence of discrete energy states of atoms.
1919	The proton is discovered.
1920	Rutherford proposes the existence of the neutron.
1923	Louis de Broglie proposes that electrons have a wave nature.
1926	Max Born, Werner Heisenberg and Pascual Jordan develop the theory of mechanics.
1927	Werner Heisenberg develops the uncertainty principle.
1932	James Chadwick experimentally confirms the existence of the neutron.

On Christmas Eve 1899, just a few days before the beginning of the new century, Max Planck first described the energy of atoms in terms of packets called 'quanta'. Looking back now, many physicists regard this moment as the birth of what we now refer to as modern physics. This new form of physics arose from the physics discoveries of the previous four hundred years or so — what is generally known now as classical physics.

The nineteenth century hummed with discovery, and the sweeping changes that came with the Industrial Revolution in Europe led many to believe that Science had at last mastered the natural world. Building upon the prodigious work of Isaac Newton and his contemporaries in the seventeenth century who had finally drawn together the threads of motion, mass and force to explain gravity and the movement of heavenly bodies, the new scientists such as Michael Faraday and H F E Lenz went on to explain electricity and magnetism. In the early 1800s, Thomas Young in England and Augustin Fresnel in France confirmed the wave nature of light, settling a long-standing dispute as to the nature of light and overturning the favoured theory that light was made up of particles. Around 1870, James Clark Maxwell theorised that accelerating electric charges would produce electromagnetic radiation, the existence of which was first demonstrated by Heinrich Hertz in 1887; Hertz later went on to confirm that light itself was a form of electromagnetic radiation.

Another aspect of light studied by early physicists such as J Fraunhofer was that of the characteristic spectra that gases produced when heated or when an electric discharge was passed through them. We will look at this in a little more detail as spectra of gases play an important part in the development of quantum theory.

The invention of an efficient vacuum pump by Heinrich Geissler in 1855 led to the discovery of a different type of electric discharge that was able to travel through a tube that had been evacuated to a very low pressure. The nature of these cathode rays, as they were called, was not explained until 1897 when J J Thomson identified them as being made up of negative particles called electrons.

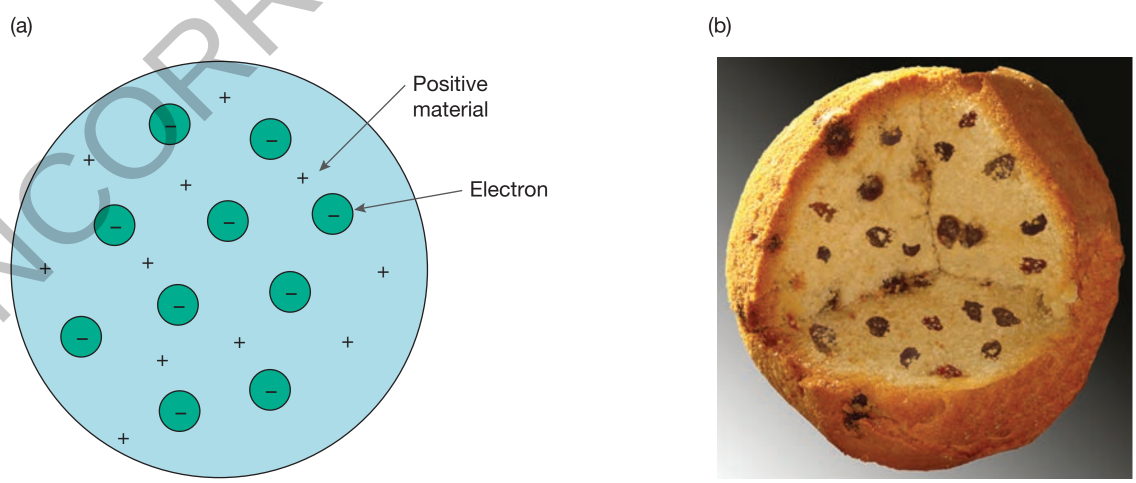
However, for all the discoveries that were made, the end of the nineteenth century left many questions still unanswered and had even produced new questions. Some optimistically declared that these were merely minor details that would be eventually cleared up. In fact, what had been deemed ‘minor details’ led to the development of modern physics and an entirely new way of looking at the universe.

13.3.2 Rutherford’s model of the atom

A precursor to the Rutherford model of the atom was the J.J. Thomson model of the atom, often referred to as the ‘plum-pudding model’. Thomson was able to demonstrate that a mysterious radiation known at the time as ‘cathode rays’ consisted of negatively charged particles with a charge-to-mass ratio of approximately $1.8 \times 10^{11}\ \mathrm{C\,kg^{-1}}$. This was achieved by passing a beam of ‘cathode rays’ through a magnetic field and observing the beam to curve, indicating the rays were, in fact, negatively charged particles. He named these particles ‘electrons’.

Thomson’s discovery led him to a new model of the atom. The atom, according to Thomson, must consist of a positively charged fluid with his negatively charged electrons scattered throughout the atom. The model was known as the ‘plum pudding’ model of the atom because Thomson envisioned that the electrons were strewn through the positive body of the atom just as plums are in a plum pudding.

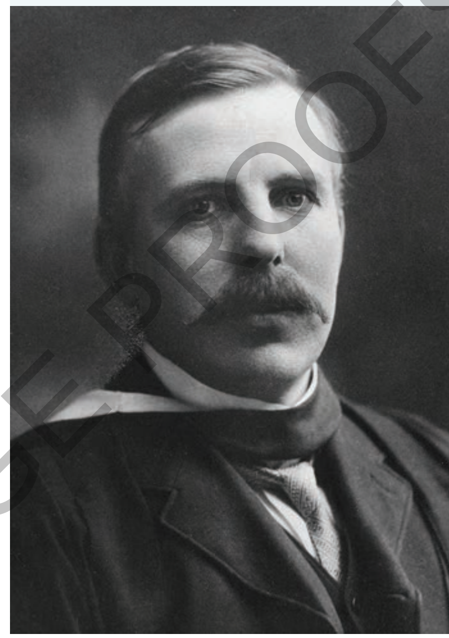
FIGURE 13.21 (a) Thomson’s plum pudding model of the atom. (b) Distribution of plums in a plum pudding.



One of the younger physicists who assisted J J Thomson in his electron experiments was the New Zealander Ernest Rutherford. After leaving Thomson's laboratory, Rutherford went to McGill in Montreal, Canada, where he did extensive study of how alpha particles (a form of radiation) were deflected by a variety of materials and how the paths of alpha particles were affected by electric fields.

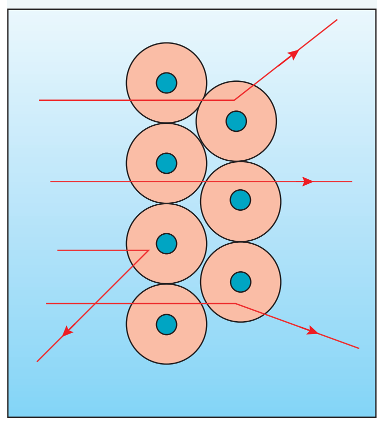
Rutherford did nothing more with alpha particle scattering until he moved to Manchester, England, in 1907, where he inherited Hans Geiger, a German physicist who specialised in the detection of radioactivity, as his assistant. Rutherford was inspired to return to his investigations of the scattering of alpha particles, this time by very thin metal foils. As part of these experiments, Rutherford suggested to an undergraduate student named Ernest Marsden (who was being trained in radioactive detection techniques by Geiger) that he should investigate if alpha particles fired at thin metal foils were deflected in the same way as they were by other materials. Rutherford expected that all of the alpha particles would pass through the thin foils with only a small deflection from their original path — a matter of a few degrees of angle change. However, Marsden observed that, while most of the alpha particles fired at a thin gold foil were deflected from their path by a small amount (if at all), a very small fraction of the alpha particles (about 1 in 8000 particles) were deflected by angles greater than 90°; some of these were found to be reflected back in the direction from which they had come! In one of the last lectures that Ernest Rutherford ever gave, he described his reaction to Marsden's discovery of deflection of alpha particles through large angles as 'the most incredible event that has ever happened to me in my life. It was almost as incredible as if you had fired a fifteen-inch shell at a piece of tissue paper and it came back and hit you'.

FIGURE 13.22 Ernest Rutherford (1871–1937)



Ernest Rutherford was awarded a Nobel Prize for Chemistry in 1908. The award that year was a matter of intrigue. In an attempt to award Nobel prizes to two atomists (Planck and Rutherford) in the same year, Dr Arrhenius, Director of the Nobel Institute for Physical Chemistry, arranged for Rutherford to be nominated for the Chemistry prize and for that prize to be determined before the Physics prize. In the end, Planck was opposed for the Physics prize, which he was eventually awarded ten years later.

FIGURE 13.23 The deflection of alpha particles by atoms in a thin gold foil in Marsden's experiment



Looking at the results of the experiments of Geiger and Marsden, Rutherford realised that they were similar to those that you would expect when two charged bodies interacted — an electrostatic force arising between the foil atoms and the alpha particles or if one mass had collided elastically with another. However, according to Thomson's model of the atom, electrons were small, negatively charged and distributed evenly through a positive material. Rutherford knew that such small charges as the electrons could have little electrostatic effect on the much larger alpha particles. It came to him that the distribution of the positive and negative charge in an atom was not uniform at all, but that the majority of the atom was made up of empty space with all of the positive charge located in a mass in the centre with the much smaller negative charges around the outside.

Two years after Geiger and Marsden published a paper on the deflection of alpha particles by thin metal foils, Rutherford explained their results by proposing a nuclear atom. In this model, electrons orbited around the outside of a much more massive positive centre or 'nucleus' much as the planets orbit the sun. (For this reason, the Rutherford model is sometimes referred to as the 'planetary model of the atom'.) This large nucleus contained 99.9% of the atom's overall mass. When the alpha particles passed through the empty regions of the atoms far from the nucleus, they were deflected from their paths by only a small amount; the closer to the nucleus their path was, the greater the electrostatic repulsion that they experienced and, so, the greater the deflections.

On the basis of his nuclear model, Rutherford calculated the relative numbers of alpha particles that would be scattered through different angles. When Geiger began a series of careful experiments in which he made observations of the number of alpha particles scattered through different angles, his experimental results matched Rutherford's predictions. Rutherford's model of the atom replaced that of Thomson.

FIGURE 13.24 The apparatus used in 1911 to study alpha particle scattering. In this version, the microscope and scintillation screen can be rotated to observe the alpha particles at different angles. Polonium was used as the alpha particle source, the metal foil used was gold and the apparatus was evacuated.

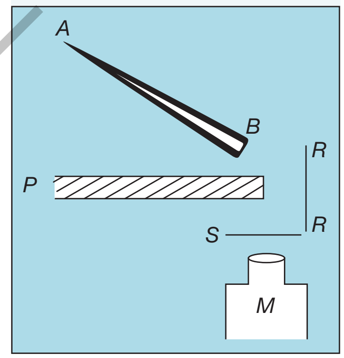
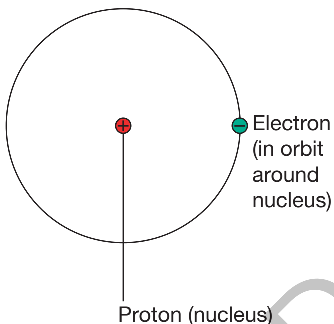


FIGURE 13.25 Diagram of the Rutherford model of the atom of hydrogen



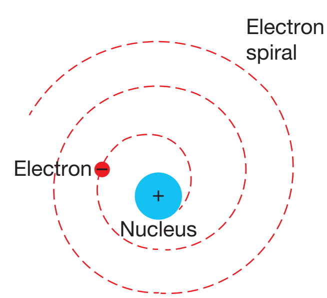
The radius of a hydrogen atom is about 2.1×10^{-11} m. The radius of a proton is about 0.85 femtometres (0.85×10^{-15} m). Physicists sometimes call this unit a fermi, named after Enrico Fermi. The ratio of the radius of this atom to the radius of its nucleus is about 2.5×10^4. This would make it very difficult to construct an accurate scale model of an atom in your laboratory. If your laboratory was 10 m across and this represented the diameter of the atom, the diameter of the nucleus would have to be 4×10^{-4} m or 4 tenths of a millimetre in diameter!

13.3.3 Limitations of the Rutherford model of the atom

While Rutherford's model provided a better explanation of observed experimental results, it had a number of shortcomings. First, if the electrons were in orbit around the nucleus, they would be accelerating and so, according to Maxwell's theories of electromagnetism, they would be emitting electromagnetic radiation. However, in giving off this radiation, the electrons would then have to be losing energy and their orbits would deteriorate until they finally spiralled into the positive nucleus. If this were the case, then:

- The frequency of the radiation given off by the electrons as they spiralled closer and orbited faster would become increasingly larger. In reality, this was never observed.
- The atoms would be unstable. Once again, this was not true as the general stability of matter indicates that atoms themselves are also very stable.

FIGURE 13.26 Rutherford's model implied that electrons would lose energy and spiral into the nucleus.



The second difficulty that arose from the Rutherford model was that it was unable to explain why atoms emitted characteristic spectral lines. This was a puzzle that had yet to be solved.

13.4 The neutron

13.4.1 The discovery of the neutron

After the discovery of the nucleus, it seemed logical to assume that the nucleus contained protons and electrons. It was possible to explain radioactive transmutations in terms of emission of alpha and beta particles from the nucleus of protons and electrons. However, there were major problems with the idea of a nucleus containing these constituents.

In 1920, Rutherford proposed that a neutral particle, with mass comparable to that of a proton, must be another constituent of the nucleus. He named this particle a neutron. In future research he and James Chadwick (1891–1974) continued to look out for any result that would suggest the existence of such a particle.

Experiments involving artificially induced radioactivity

The radioactivity that we have encountered so far has been associated with natural alpha, beta and gamma emitters. Rutherford was the first to use alpha particles to produce nuclear reactions.

The first artificially induced transmutation

In 1919, Rutherford bombarded nitrogen gas with alpha particles from bismuth-214. A positively charged particle that was more penetrative than an alpha particle was produced. This particle was identified as a proton.

What had occurred, as shown in figure 13.27, was that the alpha particle had combined with the nitrogen nucleus and a proton had been emitted. The alpha particles from the bismuth-214 source were able to approach the nucleus very closely and occasionally make contact with it. The equation for this reaction is:

$$^{4}_{2}\text{He} + {}^{14}_{7}\text{N} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H}$$

PHYSICS FACT

Alpha-particle-induced nuclear reactions

When the first alpha particle scattering experiments were performed, low-energy alpha particles were used and those that approached a gold nucleus (containing 79 protons) were strongly repelled. In the alpha-particle-induced reaction with nitrogen, the alpha particles had a much higher energy than those used in the early experiments and there was only a weak repelling force from a nitrogen nucleus that contained only 14 protons. An energetic alpha particle was able to make contact with the nitrogen nucleus.

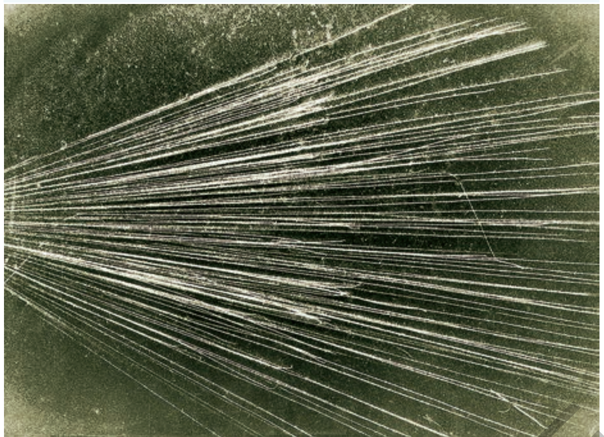
Various writers have commented that Rutherford was fortunate that he did not use a source of very powerful alpha particles when he performed his first alpha particle scattering experiments!

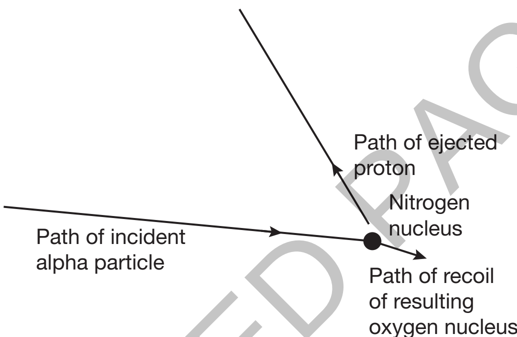
An artificially induced radioactivity

In 1930, Bothe and Becker (in Germany) fired alpha particles at beryllium and found that a highly penetrating radiation was produced. The radiation seemed to be similar to gamma rays (high-energy photons) but it was much more highly penetrating than the gamma rays previously observed. It was found to have an energy of about 10 MeV, again much higher than that previously observed for gamma rays.

In France, Frédéric Joliot (1900–1958) and his wife Irène Curie (1897–1956) (daughter of Marie Curie), studied this mysterious radiation and let it fall on a block of paraffin. Paraffin is a hydrocarbon very rich in hydrogen atoms. They found that the radiation knocked protons (hydrogen nuclei) from the paraffin (see figure 13.28). The energy of the protons was about 5 MeV. Of course, now that charged particles (protons) were involved, it was much easier to determine their properties. They also found that many more protons than expected were emitted from the paraffin. If gamma rays had been responsible, their very high penetrating power would have resulted in fewer interactions with protons.

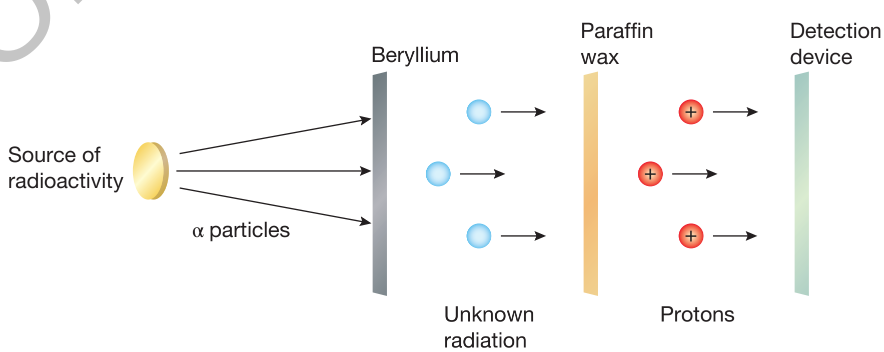
FIGURE 13.27 The photograph shows alpha particle tracks through a cloud chamber filled with nitrogen gas. The diagram helps to identify an event where a nitrogen nucleus has been struck by an alpha particle. A proton is ejected upwards and the resulting oxygen nucleus recoils downwards.





The high energy of the protons (5 MeV) was a problem because applying the conservation of energy and conservation of momentum to the collision between a gamma ray and a proton yielded a value for the incident gamma ray of at least 50 MeV. This was a major dilemma because the energy of the incident alpha particles was only about 5 MeV. In other words, if this was the correct interpretation, there had to have been a tenfold increase in energy in the interaction!

FIGURE 13.28 The reaction of alpha particles with beryllium produced a mysterious radiation that knocked protons out of paraffin.



PHYSICS FACT

Rutherford's prediction of the neutron

In his Bakerian lecture of 1920, Rutherford had suggested that 'it may be possible for an electron to combine much more closely with the hydrogen nucleus than is the case in the ordinary hydrogen atom'. He later used the term neutron. It is worth noting that Rutherford's conjecture about the existence of the neutron had not received wide publication and it had not been read by either Joliot or his wife. Some years later Joliot commented on the fact that he had not read Rutherford's Bakerian lecture and that, had he done so, it was possible or probable that he and his wife would have identified the neutron before Chadwick.

13.4.2 Chadwick identifies the neutron

Just over two weeks after reading the paper of the Joliot–Curies, James Chadwick (1891–1974) had completed his work and submitted a paper on 'Possible existence of a neutron' (1932). In that time Chadwick applied conservation of energy and conservation of momentum to the interaction of a neutral particle (of mass similar to that of a proton) with a proton. Chadwick made measurements of the recoil of nuclei of hydrogen and nitrogen after interactions with his proposed neutron. The measurements were difficult but led to the mass of a neutron being calculated to be 1.15 times that of a proton.

At this time (1932), there was doubt expressed about whether or not the conservation laws of classical physics would apply to nuclear processes. Some leading physicists were adamant that they would but others, including Bohr, thought otherwise. In fact it was 1936 before Bohr dropped his ideas of non-conservation of energy.

As Chadwick's neutron identification depended on the conservation laws and there was doubt expressed about them at the time, he concluded his paper 'Up to the present, all the evidence is in favour of the neutron . . . [unless] the conservation of energy and momentum be relinquished at some point'.

The nuclear equation for the reaction of alpha particles with beryllium is:

$${}^{9}_{4}\text{Be} + {}^{4}_{2}\alpha \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}.$$

There were no naturally occurring neutron emitters but now, with a high-energy alpha particle source (such as polonium) and some beryllium, it was possible to produce neutrons and conduct neutron scattering experiments.

PHYSICS FACT

Problems with electrons and protons in close association

It is worth noting that there are major difficulties with the concept of electrons and protons in close association either as a single particle (the neutron) or generally in the nuclei of atoms. The masses of atoms could not be explained in terms of numbers of protons and electrons. Another problem involved the de Broglie wavelength of an electron. How could an electron with an energy of a few MeV be confined to a region with a radius of 5×10^{-15} m when its de Broglie wavelength was large compared to this radius?

These difficulties were overlooked at the time because, after all, an alpha particle seemed to be 4 protons and 2 electrons combined very tightly together.

13.5 Review

13.5.1 Summary

- Cathode ray tubes were used to investigate the properties of cathode rays.
- Cathode rays were found to be negatively charged particles.
- Charged parallel plates produce a uniform electric field.

- The strength of a uniform electric field, E, in volts per metre, produced by parallel plates, separated by a distance, d, and charged by an applied voltage, V, is given by:

$$E = \frac{V}{d}$$

- Millikan showed that charge came in discrete packets, multiples of the smallest amount: 1.6×10^{-19} C. This was achieved by having oil drops in vertical equilibrium so that an upward electric force balanced a downward gravitational force such that $qE = mg$, allowing $q = \frac{mg}{E}$ to be used to determine the charge, q.
- A charged particle moving with a velocity, v, at an angle, θ, through a magnetic field of strength, B, experiences a force, F. The magnitude, in Newtons, is given by:

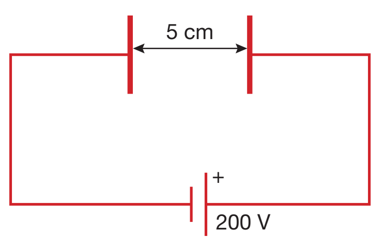
$$F = qvB \sin\theta.$$

F, v and B are all vector quantities, and each has a direction associated with it.
- Thomson's experiment, using perpendicular electric and magnetic fields, allowed him to determine the charge-to-mass ratio of an electron. The value he determined was $1.759 \times 10^{11}\ \text{C kg}^{-1}$.
- The discovery of cathode rays, which were identified by Thomson to be electrons, led Thomson to a new model of the atom; one which contained electrons immersed in a positively charged fluid.
- Rutherford's model of the atom had a central positively charged mass called the nucleus that was orbited by electrons.
- The Rutherford model of the atom explains alpha particle scattering very well. The planetary model of electron orbits necessary for the Rutherford model means that atoms self-destruct due to accelerating charged particles emitting light in accordance with Maxwell's equations.
- The properties of the nucleus could not be explained by assuming it contained protons and electrons. The existence of a new particle was predicted; this new particle was called the neutron and it was discovered in 1932 by Chadwick.

13.5.2 Questions

1. Why can cathode rays be observed and manipulated within a vacuum tube and not in air?
2. Look up the meaning of 'conservation of charge'. In a discharge tube, cathode rays were formed and moved from the cathode (the negative electrode). If these rays carried an electric charge, where was the corresponding amount of positive charge?
3. Draw the electric field lines between a positive and negative charge of equal magnitude. In which area is the electric field strongest?
4. Calculate the electric force on a charge of 1.0×10^{-6} C placed in a uniform electric field of $20\ \text{N C}^{-1}$.
5. Draw the electric field lines between two parallel plates placed 5.0 cm apart.
6. The electric field between parallel plates can be considered 'uniform' only in the region between the plates that is well away from the edges of the plates. What is meant by this statement?
7. A pair of parallel plates is arranged as shown in figure 13.29. The plates are 5.0 cm apart and a potential difference of 200 V is applied across them.

FIGURE 13.29



Data:

Charge on electron = -1.6×10^{-19} C

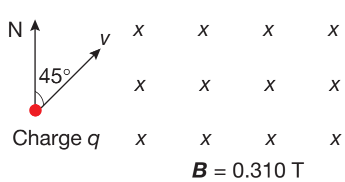
Mass of electron = 9.1×10^{-31} kg

Mass of proton = 1.67×10^{-27} kg

(a) Calculate the magnitude and direction of the electric field between the plates.
(b) Calculate the force acting on an electron placed between the plates.
(c) Calculate the force acting on a proton placed between the plates.
(d) Explain why these two forces are different.
(e) Calculate the work done in moving both the electron and the proton from one plate to the other.

8. Negatively charged latex spheres are introduced between two charged plates and are held stationary by the electric field. Each sphere has a mass of 2.4×10^{-12} kg and the strength of the field required to counter their weight is 4.9×10^{7} N C^{-1}. Sketch this arrangement, identifying the positive and the negative plate, and determine the charge on the spheres.
9. Two parallel plates are separated by a distance of 10.0 cm. The potential difference between the plates is 20.0 V.
   (a) Calculate the electric field between the plates, assuming the field to be uniform.
   (b) A charge of $+2.0 \times 10^{-3}$ C is placed in the field. Calculate the force acting on this charge.
10. A beam of electrons moves at right angles to a magnetic field of flux density 6.0×10^{-2} T. The electrons have a velocity of 2.5×10^{7} m s^{-1}. What is the magnitude of the force acting on each electron?
11. A stream of doubly ionised particles (missing two electrons and therefore carrying a positive charge of twice the electronic charge) move at a velocity of 3.0×10^{4} m s^{-1} perpendicular to a magnetic field of 9.0×10^{-2} T. What is the magnitude of the force acting on each ion?
12. An electron is travelling at right angles to a magnetic field of flux density 0.60 T with a velocity of 1.8×10^{6} m s^{-1}. What is the force experienced by the particle?
13. Given that the mass of the electron in question 3 is 9.1×10^{-31} kg, what is the acceleration of the particle in the direction of the force acting on it?
14. A charge of 5.25 mC, moving with a velocity of 300 m s^{-1} due north east, enters a uniform magnetic field of 0.310 T directed vertically downwards, into the page. Calculate the magnetic force on the charge.

FIGURE 13.30



15. If charged particles enter a magnetic field at angles other than at right angles, describe their path.
16. List the properties of cathode rays which can be described:
    (a) as wave motion
    (b) by a particle model.
17. Explain how the properties of cathode rays were demonstrated using the evacuated tubes in which a metal cross was mounted in the path of the rays, and in which a small paddle wheel was able to roll along glass rails.

18. Describe the path of an electron when it enters the region between parallel plates across which a potential difference of 1500 V is applied. Sketch the arrangement for an electron entering with a horizontal velocity of 2.4×10^4 m s^{-1} at right angles to the electric field.
19. Describe the conditions needed for an electron entering a magnetic field to undergo uniform circular motion.
20. In a tube similar to that used in the Thomson's electromagnetic experiment, a magnetic field of 1.00×10^{-2} T is sufficient to allow the electrons to pass through the electric deflection plates. The plates are 10 mm apart and have a potential difference of 300 V across them.
    (a) What is the strength of the electric field between the plates?
    (b) What was the speed of the electrons as they entered the region between the plates?
    (c) What was the strength of the magnetic force acting on the electrons?
21. What is the evidence to support the claim that an atom consists of a small positively charged nucleus whose size is approximately $\frac{1}{10000} \times$ the size of an atom?
22. What is the problem that arises with an atomic model where electrons are in a planetary-type circular orbit around the nucleus?
23. Write out the equation for the nuclear reaction that Chadwick made use of to produce free neutrons.
24. There are two fundamental principles in physics that were used to assert that a neutral particle of mass similar to that of a proton must exist. What are the names of these two fundamental principles?
25. Once the neutron was isolated in the early 1930s, why did the atomic masses of elements make more sense?
26. Why are neutrons difficult to detect?
27. Why is the existence of a neutron inside a nucleus necessary to better explain beta decay?

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DISCHARGE TUBES

Aim

To observe the effect that different gas pressures have on an electric discharge passed through a discharge tube.

Apparatus

power pack
two plug–plug leads
one set of discharge tubes (with varying pressures)
induction coil
two plug–clip leads

Theory

The high voltage produced by the induction coil is applied across the terminals inside the discharge tubes. One plate (the cathode) becomes highly negative and releases a ray (cathode ray or electron). The electron passes through the gas in the tube and excites electrons in the atoms of the gas contained in the tube. The pressure of the gas determines the density of the atoms and therefore the nature of the collisions which take place between the electrons and atoms. Therefore, different discharge effects under different pressures can be observed (refer back to figure 13.4).

Method

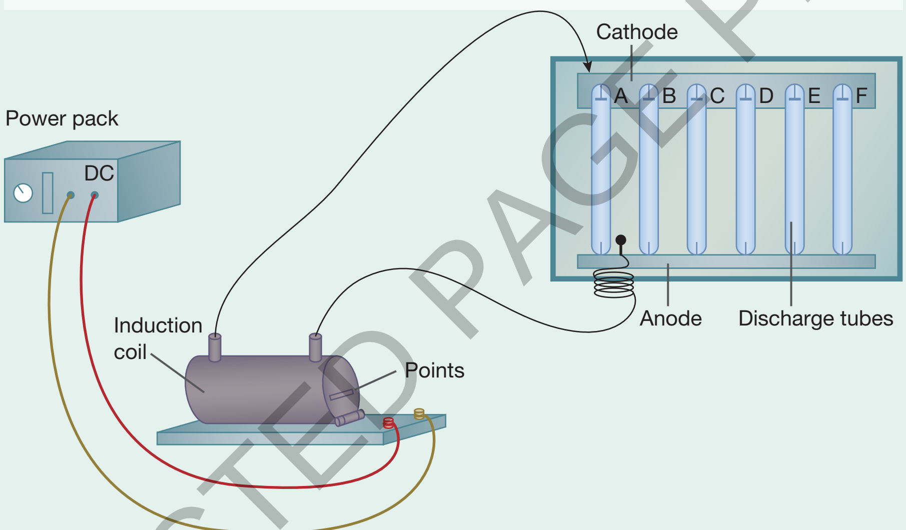
Safety note

When the induction coil is connected to the discharge tube, X-rays are produced. However, it is the cathode rays hitting the glass or metal within the discharge tube that creates the X-rays, not the induction coil. If the experiment uses a minimum operating voltage these X-rays will be of a low energy and are significantly reduced after passing through the glass.

We need to deal with induction coils with extreme care because of the high voltages associated with them. Your teacher will set up the equipment related to the induction coil.

1. Attach the induction coil to the power pack using the two plug–plug leads. Adjust the points on the induction coil to obtain a continuous spark from the coil. Switch off the power pack.

FIGURE 13.31 Set-up for practical activity 10.1



2. Set the power pack at the correct setting for the induction coil (usually 6 volts) and turn it on.
3. Attach the negative terminal of the induction coil to the cathode of the discharge tube marked with the highest pressure (40 mmHg) and attach the positive terminal to the other end as shown in figure 13.31. Switch on the power pack.
4. Sketch a diagram of the pattern observed in this tube and describe it carefully.
5. Repeat the above procedure using each of the discharge tubes and see if you can observe streamers, Faraday's dark space, cathode glow, Crookes' dark space, striations and the positive column. Carefully describe each pattern, identifying each of the effects mentioned. (Tubes to be used should be 40 mmHg, 10 mmHg, 6 mmHg, 3 mmHg, 0.14 mmHg and 0.03 mmHg. These are represented as A, B, C, D, E and F in figure 13.31).

Questions

1. What effects were common throughout all tubes?
2. If the striations are produced by electrons (cathode rays) striking atoms and causing light to be released, give an explanation for the occurrence of variation in the patterns for different pressures.

PROPERTIES OF CATHODE RAYS

Aim

To determine some of the properties of the rays which come from the cathode of a discharge tube.

Apparatus

two power packs
two plug–plug leads
one pair of magnets

induction coil
four plug–clip leads
discharge tubes (maltese cross, electric plates, rotating wheel, screen display)

Theory

This experiment will most likely be performed as a class demonstration by your teacher. The discharge tubes used are illustrated in figure 13.3 and are similar to those Sir William Crookes would have used.

Method

Before starting, it would be advisable to read the 'Analysis' section of this experiment so as to plan what you should record during the experiment.

1. Connect the power pack to the induction coil and set it at 6 volts. Adjust the points on the induction coil so that a strong steady spark is being produced, as in practical activity 13.1.
2. Connect the terminals of the induction coil to the discharge tube containing the maltese cross (Crookes' tube). Observe the end of the tube containing the cross when the cross is down and when it is up.
3. Replace the Crookes' tube with the tube containing the electric plates and connect the terminals of the plate to its high DC voltage supply. Observe the effects of the electric field on the cathode rays.
4. Connect the tube with the fluorescent screen display to the induction coil and record the effect of placing a set of bar magnets around the cathode rays as shown in figure 13.3.
5. Finally, attach the tube containing the glass wheel on tracks to the induction coil and observe the effects that the cathode rays have on the wheel when the tube is horizontal.

Analysis

1. For each of the tubes placed in the circuit, sketch a diagram of the tube and the effect caused by the cathode rays.
2. Using the laws of electromagnetism, determine the charge that is evident on the cathode rays.

Questions

1. What are five properties of cathode rays which can be deduced from this experiment?
2. From these results, can we conclusively say that the cathode rays are electrons? Why or why not?