

7

Magnetic fields

PRIOR KNOWLEDGE

Before you start, make sure that you are confident in your knowledge and understanding of the following points:

- Magnets have two poles: a north-seeking pole (N, or north pole) and a south-seeking pole (S, or south pole).
- A magnetic field is a region where the magnet exerts a force on other magnets or magnetic materials, even if they are not in contact.
- A magnet attracts magnetic materials (e.g. iron) placed in its magnetic field provided the field is non-uniform. The magnet attracts another magnet if unlike poles are facing (north–south), and repels another magnet if like poles are facing (north–north or south–south).
- A current-carrying wire creates a magnetic field, which encircles the wire carrying the field.
- An electromagnet can be made by making a coil of wire and passing a current through it. The strength of an electromagnet increases if the current in the wire increases, if more turns are added to the coil, and if a magnetic core is placed inside the coil.
- Electromagnets made using a soft magnetic core (e.g. iron) lose their magnetism if the current is turned off. If a hard magnetic material is used (e.g. steel), the electromagnet retains its magnetism when the current is turned off.

TEST YOURSELF ON PRIOR KNOWLEDGE

- 1 Magnetism causes a non-contact force. Give examples of two other non-contact forces, and what these forces affect.
- 2 Describe how to make a strong, temporary magnet.
- 3 A compass needle is magnetic. Explain why the north pole of a compass needle is attracted to the Earth's geographic North Pole.
- 4 Iron can be magnetised if it is stroked repeatedly in one direction using a magnet. Iron atoms behave like mini-magnets. Magnetic domains are regions where groups of atoms line up in one direction. Explain how iron can be magnetised in terms of magnetic domains.

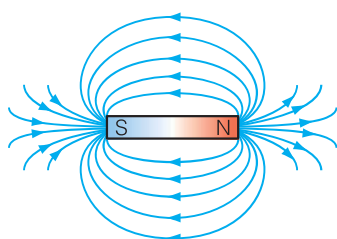
Experiments using radiation up to 10 billion times brighter than sunlight are carried out at the Diamond Light Source facility in Oxfordshire (Figure 7.1). Diamond is a synchrotron which accelerates beams of electrons to the speed of light. Very strong magnets direct the electrons through a pipe 56 Zm circumference and under ultra-high vacuum. The electrons lose energy, emitted as synchrotron light, as they change direction in the magnetic field. Synchrotron light ranges from infrared radiation to x-rays.

Electrons also travel through magnets set out in arrays called insertion devices. These are even stronger magnets, some of which are super-conducting. Since

the direction of the magnetic field repeatedly changes, the electrons are forced to wiggle through the device. The electrons release energy when they change directions, either as extremely intense electromagnetic radiation turned into specific frequencies, or a broad spectrum of radiation, depending on the arrangements of the magnets.



Figure 7.1 Diamond in Oxfordshire.



field lines around a bar magnet

Figure 7.2 Flux lines for a bar magnet. The flux density is highest at the poles, where the field is strongest.

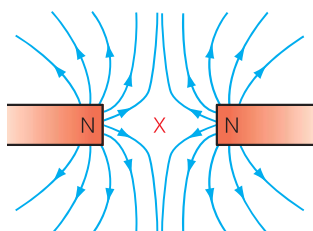


Figure 7.3 The combined field from two bar magnets. Neutral points are marked X.

Magnetic flux lines

Magnets have a north pole and a south pole, so we call magnets dipoles. A *magnetic field* is the region where a magnet exerts a force on objects made from magnetic materials, or on other magnets. We represent the magnetic field using arrows, or *flux lines*, to indicate the direction and strength of the field in the region surrounding the magnet. The rules for drawing magnetic flux lines, electric field lines and gravitational field lines are similar. For magnets, these rules are as follows:

- Flux lines represent the direction of the force experienced by the north pole of a magnet at any point in the magnetic field. They run from the north pole to the south pole.
- A magnetic field is strongest where its flux density is highest, and this is shown as flux lines closest together (Figure 7.2).
- A magnetic field with twice the strength is drawn with twice the number of flux lines per unit area in the same region.
- The magnetic field of more than one magnet is the combined field of the individual magnets.
- Flux lines never cross.
- If there is more than one magnet, the magnetic fields cancel out in some places and there is a neutral point (Figure 7.3).

A magnet freely suspended in a magnetic field will align itself with the field.

Magnetic flux density The number of magnetic flux lines that pass through an area of 1 m^2

Tesla The flux density that causes a force of 1 N on a 1 m wire carrying a current of 1 A at right angles to the flux.

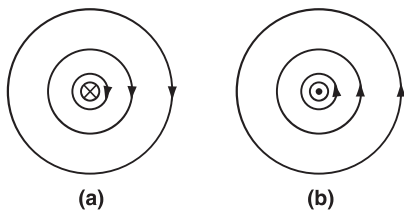


Figure 7.4 The magnetic flux of a current-carrying wire: (a) with the current flowing into the page and (b) with the current coming out of the page.

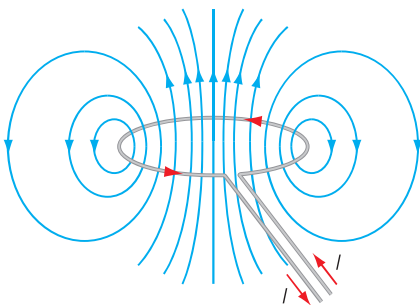


Figure 7.6 The magnetic field for a current-carrying loop of wire.

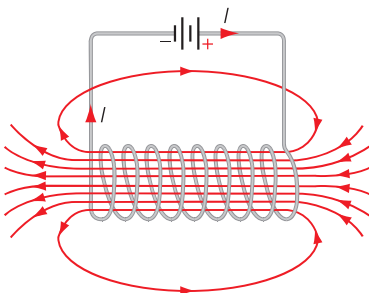


Figure 7.7 The magnetic field for a solenoid.

The strength of a magnetic field

The strength, or intensity, of a magnetic field is its **magnetic flux density**, B , also known as a B -field. Magnetic flux density is measured in **teslas** (T). Magnetic field or flux lines are a model that helps us to visualise the field. You will learn more about magnetic flux, ϕ , in Chapter 8.

If you look at a diagram of a magnetic field, you can see that the flux lines are closer together in places (for example, at the poles of a bar magnet as shown in Figure 7.2). You can tell that the magnetic field and the force produced by the magnet are stronger at the poles because this is where the flux lines are closer together.

Magnetic fields from current-carrying wires

Moving charges cause a magnetic field, which we describe using flux lines. The magnetic flux around a current-carrying wire is shown as concentric circles, indicating the magnitude and direction of the flux pattern. Moving away from the wire, flux lines are further apart because the field gets weaker. If you look at the wire with the conventional current flowing away from you, the flux lines circle the wire in a clockwise direction. Symbols inside the wire indicate the current direction: $\otimes$ indicates a current flowing away from you (Figure 7.4a) and $\odot$ indicates a current flowing towards you (Figure 7.4b). The combination of flux lines for a loop of wire is shown in Figure 7.5.

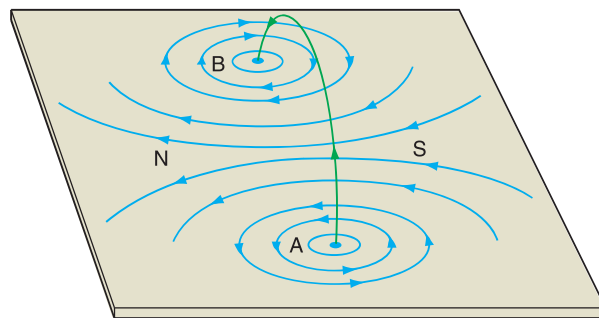


Figure 7.5 A magnetic field circles a current-carrying wire.

A **solenoid** is a current-carrying coil of wire that produces magnetic flux (Figure 7.7) – this is also described as an electromagnet formed from a coil of wire. The magnetic flux outside a solenoid is similar to the magnetic flux for a bar magnet, with the north pole at one end of the coil and the south pole at the other end, depending on the current direction.

A current-carrying wire in a magnetic field moves because a force acts on it. The magnetic field making the wire move is called a **catapult field**. The catapult field is due to the combined effect of the current-carrying wire's flux and the static flux. Figure 7.8 shows the separate fluxes, and how they combine to form a catapult field.

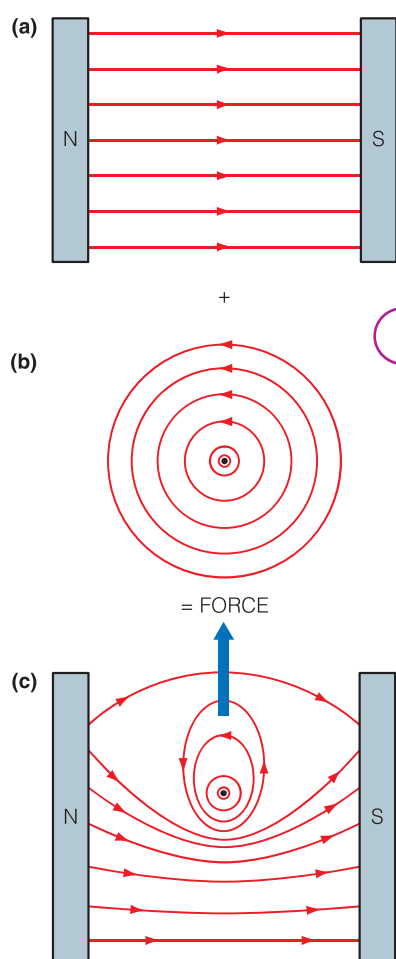


Figure 7.8 (a) A uniform magnetic field. (b) The field around a current-carrying wire. (c) The catapult field. The force is from the strong to the weak field.

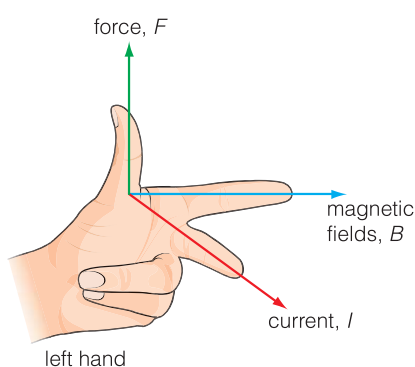


Figure 7.9 Fleming's left-hand rule.

Measuring magnetic field strength

A magnetic field runs through a coil of wire as well as outside it, as shown in Figures 7.6 and 7.7. You can measure the flux density of the field using a magnetic field sensor called a Hall probe. The probe contains a slice of semiconducting material. If a current flows in the semiconductor when it is perpendicular to the magnetic flux, a potential difference is generated across the sides of the semiconductor. This potential difference is directly proportional to the flux density.

Forces on current-carrying wires

You need to know how to calculate the size and direction of a force on a current-carrying wire in a magnetic field.

Calculating the direction of the force

Magnetic flux density is a vector quantity. When the directions of the magnetic flux, the current in the conductor and the force are all at right angles to each other, Fleming's left-hand motor rule, shown in Figure 7.9, helps you see the three-dimensional arrangement of these vectors.

Hold your thumb, first finger and second finger of your left hand at right angles to each other. The **thuMb** represents the direction of the force (**M**otion), the **F**irst finger represents the direction of the magnetic **F**ield, and the **seCond** finger represents the direction of the **C**urrent.

EXAMPLE

Fleming's left-hand rule

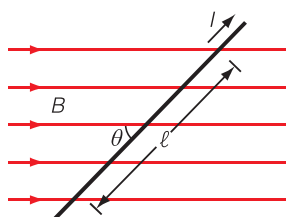
A current-carrying wire is held so that the current is into the page, and the magnetic field direction is from the bottom to the top of the page. Use Fleming's left-hand rule to find the direction of the force on the wire.

Answer

With your second finger (current) pointing into the page, and your first finger (field) pointing from bottom to top of the page, you should find that the direction of the force is from left to right.

MATHS BOX

If the wire is at an angle θ to the flux, the force on the wire is calculated using $F = BIl \sin \theta$, where θ is the angle between the wire, carrying the current, and the flux lines (Figure 7.10). When the wire lies parallel to the flux lines ($\theta = 0$), there is no force on the wire.

**Figure 7.10****Calculating the size of the force**

We can measure the flux density at any point by measuring the force exerted on a current-carrying wire at that point. The tesla is defined as the flux density that causes a force of 1 N on 1 m of a wire carrying a current of 1 A at right angles to the magnetic field. Written as an equation, this becomes

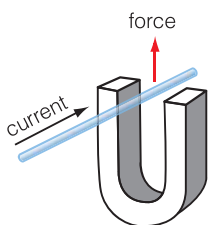
$$F = BIl$$

where F is force (N), B is magnetic flux density (T), I is current (A) and l is the length of the conductor in the field (m)

For the interested student, the Maths box gives more information about the size of the force.

EXAMPLE**Horseshoe magnet**

Figure 7.11 shows a current-carrying wire held perpendicular to the field between the two poles of a horseshoe magnet. Assume there is 2 cm of the wire in the field.

**Figure 7.11**

- 1 Calculate the magnetic flux density (B -field) for the wire if the current is 2.1 A and it experiences an upward force of 0.03 N.

Answer

The length of the wire in the field is 0.02 m. Substitute known values into the equation:

$$B = \frac{F}{Il} = \frac{0.03 \text{ N}}{2.1 \text{ A} \times 0.02 \text{ m}} = 0.71 \text{ T}$$

- 2 What current is required for the wire to experience an upward force of 0.09 N?

Answer

Rearrange the same equation to give I on the left-hand side, and substitute for the flux density, B , from the answer to part (a):

$$I = \frac{F}{Bl} = \frac{0.09 \text{ N}}{0.71 \text{ T} \times 0.02 \text{ m}} = 6.3 \text{ A}$$

- 3 The current flows into the page. State whether the direction of the magnetic field is from left to right, or right to left.

Answer

Using Fleming's left-hand rule, the field is from the right side to the left side of the page.

TEST YOURSELF

- 1 A 50 cm wire carries a current of 0.2 A. Calculate the force due to the magnetic field on the wire if it is placed:
 - a) perpendicular to the Earth's magnetic field of flux density $50 \mu\text{T}$
 - b) perpendicular to the magnetic field of an electromagnet of flux density 1.5 T.
- 2 A wire is placed at right angles to a magnetic field of flux density 6 mT.
 - a) If the force per metre of wire is 0.03 N, calculate the current in the wire.
 - b) State the value of the angle, θ , if the magnitude of the force is zero.
- 3 Copper has a density of 8960 kg m^{-3} .
 - a) Calculate the mass of an insulated piece of copper wire, 10 cm long with a cross-sectional area of $2 \times 10^{-6} \text{ m}^2$. Ignore the mass of the insulation. Two such pieces of wire are used as weights in Figure 7.12.

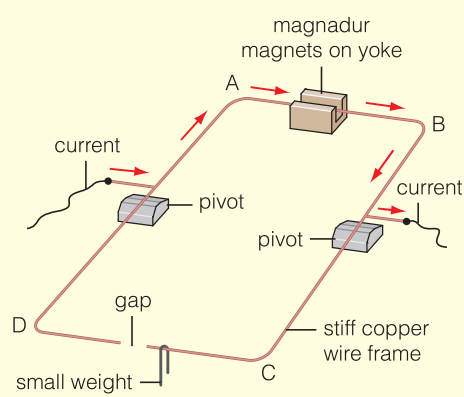
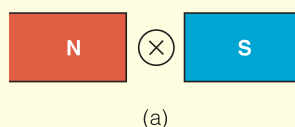
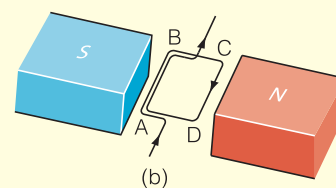


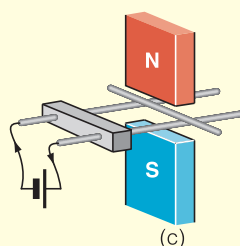
Figure 7.12



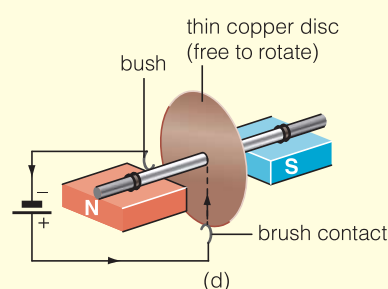
(a)



(b)



(c)



(d)

Figure 7.13

Figure 7.12 shows a current balance formed from a rectangular frame balanced on two pivots halfway along the sides AD and BC. Part of side AB lies at right angles to a uniform magnetic field. Sides AD and BC are 240 mm long. There is a small gap in side CD a small weight hangs on the wire near the gap.

The frame balances when there is no current in the circuit. When a current of 3.2 A flows through the circuit, the weight must be moved 25 mm closer to the pivot to balance the frame.

- b) Calculate the change in the moment of the copper wire when the current is off, and when the current is on.
 - c) Use your answer to part (b) to calculate the force on side AB when the current is on.
 - d) The length of the wire frame in the field is 10 cm. Calculate the flux density.
- 4 Use Fleming's left-hand rule to find the direction of the force, magnetic field or current in the four situations shown in Figure 7.13.

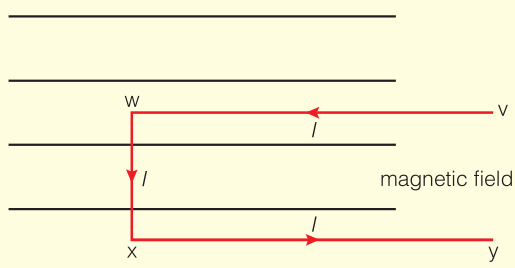


Figure 7.14

- 5 Part of a circuit, VWXY, lies in the same horizontal plane as a uniform magnetic field of flux density B . Two sides of the circuit are parallel to the flux, as shown in Figure 7.14.





a) When the current I flows through the wire, the side WX is forced upwards. State the direction of the magnetic field.

b) The length of wire, WX, in the field is 8.0 cm and this stem, experiences a force of 0.241 N when the current I is 4.6 A.

Calculate the flux density of the field, B , giving your answer to an appropriate number of significant figures.

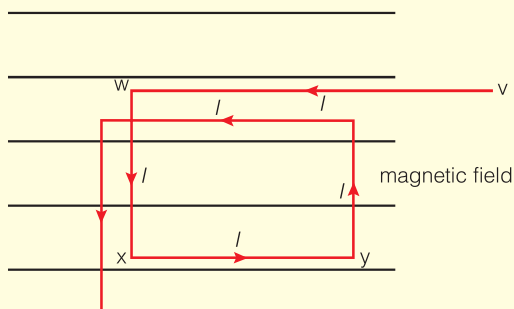


Figure 7.15

c) An extra twist of wire is made so that the wire loops and now leaves the field at X, as shown in Figure 7.15. Explain how the magnitude of the force varies in different sections of the circuit, VW, WX, XY and YV.

REQUIRED PRACTICAL 10

The force on a current-carrying conductor

Note: this is just one example of how you might tackle this required practical.

A sensitive electronic balance can be used to investigate how magnetic flux density, current and length of wire are related.

A current-carrying conductor experiences a force when it is perpendicular to a magnetic field. When magnets and a conductor are set up as shown in Figure 7.16, the electronic balance reading changes when current flows in the wire.

Newton's third law means that the magnetic force on the wire is equal in size but acts in the opposite direction to the magnetic force on the magnet. The change of reading of the balance shows the magnetic force on the magnet.

Two ceramic magnets are fixed inside a steel yoke to create a uniform field. The yoke is placed on the electronic balance. The circuit is set up as shown in Figure 7.16, and the copper wire is supported horizontally between the magnets, perpendicular to the field. The balance is zeroed, and then the circuit is switched on. Readings are taken of the current (in amps) and electronic balance reading (in grams). At least six sets of readings are taken for different current values. The effect of changing the length of wire in the field can be measured by adding an extra magnet and then re-zeroing the balance before taking readings.

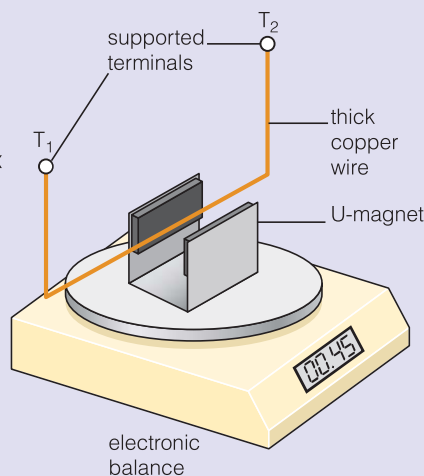
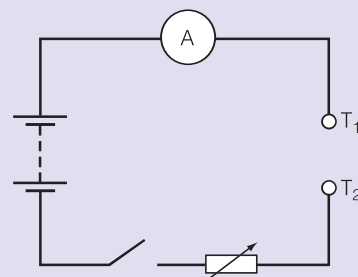


Figure 7.16 Experimental set-up for the activity, including the circuit.



Circuit for varying the current

TIP

If this experiment is actually performed, remember that the wire will heat up, so turn the circuit off between readings. A heavy-duty rheostat is also required.





You are investigating the relationship

$$F = BIl$$

Force F is calculated by converting readings in grams from the electronic balance to force. The magnetic flux density B (T) is constant if you use the same magnets and same arrangement. The length of wire between the magnets is l , measured in metres. Some sample results are shown in Table 7.1. The length of the magnets is 4.5 cm.

Current/A	Reading from balance/g	Force/N
1.0	0.46	
2.0	0.91	
3.0	1.35	
4.0	1.83	
5.0	2.30	

TIP

Tare (zero) the balance between readings as necessary.

- 1 Copy and complete the table by filling in the missing values in the force column.
- 2 Explain why it is acceptable to have a different number of decimal places for the calculations of force.
- 3 Explain why it is acceptable to have a different number of significant figures for the balance readings.
- 4 Using a graph, or otherwise, show that the magnetic flux density B is 100 mT.

Forces on a charged particle moving in a magnetic field

Charged particles moving in a magnetic field also experience a force. Old-style televisions and computer monitors use electron guns to produce beams of rapidly moving electrons in evacuated tubes, and their direction is controlled using a varying magnetic field. You can calculate the force on a single charge, Q , travelling perpendicular to a magnetic field, with flux density B .

If charge Q travels a distance l in t seconds, then the charge has a velocity $v = \frac{l}{t}$. But $I = \frac{Q}{t}$ and we can substitute for I in

$$F = BIl$$

This gives

$$F = \frac{BQl}{t}$$

Since the velocity of the charge is $v = \frac{l}{t}$, this gives

$$F = BQv$$

As before, you can use your left hand to predict the direction of the force. The thumb represents force, the first finger represents the magnetic field and the second finger represents the direction of a moving positive charge. The sign of the charge is important – a positively charged particle and a negatively charged particle will move in *opposite* directions in the same field. This is because if a negative charge moves to the left (for example), the conventional current flows to the right.

TIP

Conventional current – in many circuits the charge carriers are electrons but this is not always the case. In an electrolyte, for example, positive and negative ions move in opposite directions when a current flows.

By convention, we always show the direction of movement of positive charge carriers and so, in a simple wire circuit, this is in the opposite direction to electron flow.

Work done

When a charged particle moves at right angles to a uniform flux, the charged particle moves in a circle (Figure 7.17), because the force is always perpendicular to the motion, provided no energy is lost (for example, when the charge is in a vacuum). Work is force multiplied by distance moved in the direction of the force. Since the force is perpendicular to the motion, no work is done by the magnetic field on the charge, so the kinetic energy of the charge does not change.

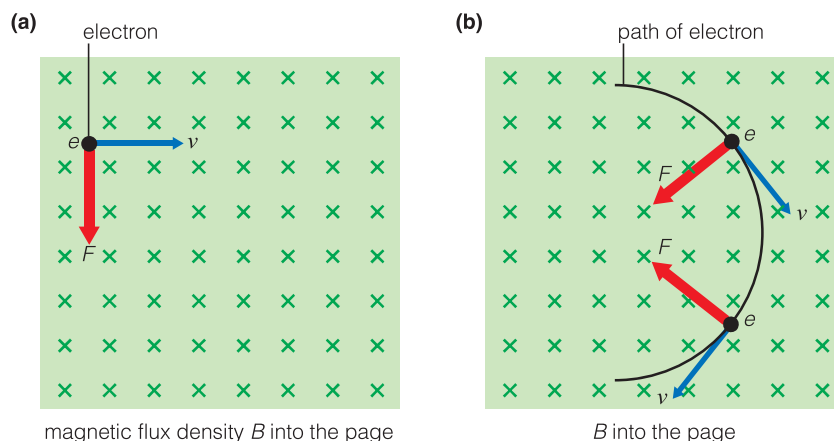


Figure 7.17 An electron travels in a circular path when it moves perpendicular to a magnetic field because the force is perpendicular to its motion.

Applying ideas about circular motion

You can link the ideas of circular motion covered in Chapter 1 with the motion of a charged particle in a magnetic field.

Since the charged particle follows a circular path in a magnetic field (Figure 7.17), we know it experiences a centripetal force. For circular motion, the centripetal force must equal the force exerted by the magnetic field. If we link the equations for centripetal force and the movement of a particle in the magnetic field, we find that

$$F = \frac{mv^2}{r} = BQv$$

Dividing both sides by v gives

$$\frac{mv}{r} = BQ$$

This equation has many applications. For situations where B and Q are constant, the radius is proportional to the momentum of the particle:

$$mv = BQr$$

EXAMPLE**Paths of ionising radiation**

Figure 7.18 shows ionising radiation travelling through a uniform magnetic field in a vacuum, at right angles to the lines of magnetic flux.

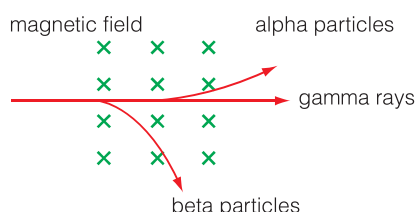


Figure 7.18

- 1 Compare the directions of motion of an alpha particle, a beta particle and a gamma ray if they move through the magnetic field as shown.

Answer

Using Fleming's left-hand rule, the magnetic field is into the page. The alpha particle is positively charged, so the force on it is upwards, and the alpha particle travels in a circular path and clockwise.

The gamma ray has no charge, so it continues to move in a straight line.

The beta particle has a negative charge, so the force on it is initially downwards, and it follows a clockwise circular path.

- 2 The diagram in Figure 7.18 is not to scale. Assuming the particles travel at the same speed, calculate the ratio of the radius of the paths for alpha particles and beta particles.

Answer

From the text,

$$\frac{mv}{r} = BQ$$

But v and B are constant, so r is proportional to m/Q . The alpha particle has a charge of $2e$, and a mass of $8000m_e$. The beta particle is an electron, with charge e and mass m_e . So the ratio is

$$\begin{aligned} \frac{\text{radius(alpha)}}{\text{radius(beta)}} &= \frac{m(\text{alpha})}{Q(\text{alpha})} \frac{Q(\text{beta})}{m(\text{beta})} \\ &= \frac{8000m_e}{2e} \frac{e}{m_e} = 4000 \end{aligned}$$

In reality, beta particles travel much faster than alpha particles, and relativistic effects increase the mass of beta particles. This means that the observed ratio is likely to be smaller. However, it shows that it is extremely difficult to deflect alpha particles using a typical school magnet.

- 3 Describe how the path will be different if the radiation travels in air, rather than in a vacuum.

Answer

In a vacuum, the charged particles travel in a circle. In air, charged particles in a magnetic field travel in a spiral, because they lose energy and slow down. Because r is proportional to v , as v decreases so does r .

You can also use the equation to find the radius r of the circle in which the charged particle travels, since $r = \frac{mv}{BQ}$. This idea is used in mass spectrometers, since charged particles with different mass/charge ratios travelling at the same speed will follow different paths.

TEST YOURSELF

- 6 Describe two situations in which a charged particle experiences no magnetic force when it is in a magnetic field.
- 7 An alpha particle travelling at 1% of the speed of light enters a field of flux density $1 \times 10^{-3} \text{ T}$. Calculate the force experienced by the particle if it travels
 - a) parallel to the direction of the magnetic flux
 - b) perpendicular to the direction of the magnetic flux.
- 8 Calculate the flux density when an electron, travelling at right angles to the field direction, at a velocity of $1 \times 10^7 \text{ m s}^{-1}$, experiences a force of $1 \times 10^{-15} \text{ N}$.
- 9 An electron enters a uniform magnetic field of flux density 0.036 T , travelling at right angles to the lines of flux. Calculate the speed of the electron if the radius of its path is 20 mm .
- 10 Figure 7.19 shows the paths of three particles in a magnetic field coming out of the page.





Compare the relative charges and speeds of the different particles A and B.

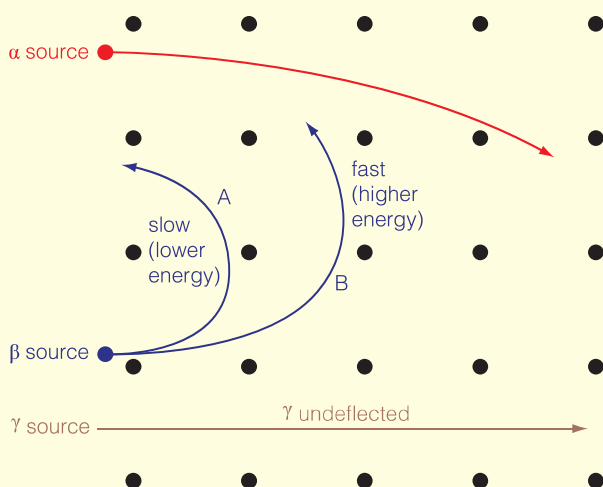


Figure 7.19

- 11 An electron travels in a circular path of radius 74 mm at right angles to a uniform magnetic field of flux density 0.43 mT.

- a) Write down an expression for the centripetal force acting on the electron.
 b) Show that the electron's speed is $5.6 \times 10^6 \text{ ms}^{-1}$.
 c) How does the radius of its path change if
 i) the kinetic energy of the electron doubles
 ii) allowance is made for the relativistic mass of the electron?

- 12 The mass of positively charged particles can be measured using a mass spectrometer. Charged particles are accelerated in a vacuum, and a velocity selector is used to select particles travelling at a specific velocity. These particles pass into a magnetic field applied perpendicular to their path and their position on a detector is recorded.

- a) Explain why particles of the same charge but different masses (e.g. M , $2M$ and $3M$) have different paths in a magnetic field.
 b) Explain how the paths would be different for the following three particles travelling in the same field: mass M and charge Q ; mass $2M$ and charge $2Q$; mass $3M$ and charge $2Q$.

Cyclotrons

Cyclotron A particle accelerator that accelerates charged particles through a spiral path using a fixed magnetic field and an alternating potential difference.

A **cyclotron** is used to force charged particles into a circular path that accelerates them to very high speeds. Cyclotrons are often used with heavier particles like alpha particles and protons. Experiments using particle accelerators investigate the structures of complex molecules like proteins, as well as sub-nuclear structures.

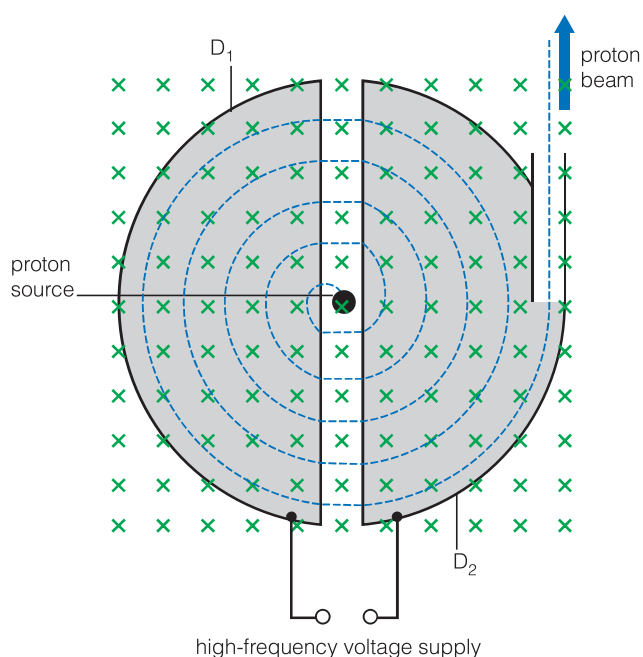


Figure 7.20 Structure of a cyclotron, a proton accelerator.

The cyclotron is formed from two semi-circular 'dees', separated by a small gap and connected to a high-frequency alternating potential difference (Figure 7.20). A strong magnetic field is applied perpendicular to the dees. The perpendicular magnetic field forces charged particles to move in a circular path inside the dees.

The particles experience a potential difference when they travel across the gap, and gain energy equal to QV (where Q is the particle's charge in coulombs, and V is the potential difference in volts). Since the particles have more kinetic energy, they move faster and accelerate to the next dee.

The ac voltage is timed to change direction every time the particles reach the gap between the dees. It must alternate to accelerate the particles each time they reach a gap. If the voltage did not alternate, the particles would follow a cycle of accelerate–decelerate–accelerate.

Particles spend the same time inside each dee, but the radius of their path increases after each gap and they travel further in the same time.

Remember that the centripetal force acting on the charged particle equals the magnetic force on the charged particle, so

$$\frac{mv^2}{r} = BQv$$

or

$$v = \frac{BQr}{m} \quad (i)$$

Because the radius is proportional to the speed of the charged particle, the particles spiral outwards as they accelerate through the cyclotron.

The time, t , spent in each dee is given by

$$t = \frac{\pi r}{v} \quad (ii)$$

because πr is half the circumference of the circle. Substituting for v in equation (ii) using equation (i) gives t , the time spent in one dee:

$$\begin{aligned} t &= \frac{\pi r}{BQr/m} \\ &= \frac{\pi m}{BQ} \end{aligned}$$

which does not depend on either radius or speed.

The effect of special relativity limits a particle's speed in a cyclotron. Particles get more massive as they travel close to the speed of light. As particles move faster and their mass increases, the time spent in each dee increases and the more massive particles get out of step with the alternating potential difference. A **synchrotron** overcomes this problem by increasing the magnetic field as the speed of the particles increases. The radius of their path remains constant even though the particles travel faster.

Synchrotron A particle accelerator that accelerates charged particles through a circular path using a varying magnetic field.

EXAMPLE

Alpha particles in a cyclotron

Alpha particles are accelerating in a cyclotron. The magnetic flux density is 0.8 T and the voltage across the gaps between the dees is 20 kV. The mass of an alpha particle is 6.64×10^{-27} kg and its charge is 3.2×10^{-19} C. Ignore relativistic effects.

- 1 Show that the frequency needed for the voltage supply to synchronise with the arrival of protons at the gaps is 6.14 MHz.

Answer

The time spent in one dee is $t = \frac{\pi m}{BQ}$; the period T for one complete circle (circling through two dees) is $2t$.

The frequency for a complete circle is $f = \frac{1}{2t} = \frac{BQ}{2\pi m}$

So

$$\begin{aligned} f &= \frac{0.8 \text{ T} \times 3.2 \times 10^{-19} \text{ C}}{2\pi \times 6.64 \times 10^{-27} \text{ kg}} \\ &= 6.14 \times 10^6 \text{ Hz} \end{aligned}$$

- 2 How many circles should the alpha particles make to reach an energy of 10 MeV?

Answer

The energy gained when an alpha particle (charge $2e$) crosses the gap is $2 \times 20 \text{ keV} = 40 \text{ keV}$. The alpha particle crosses two gaps per cycle, so it gains 80 keV ($80 \times 10^3 \text{ eV}$) per cycle. To reach an energy of 10 MeV ($10 \times 10^6 \text{ eV}$), the alpha particle must make

$$\frac{10 \times 10^6}{80 \times 10^3} \text{ circles, which is 125 circles.}$$

TEST YOURSELF

- 13** In a cyclotron, explain the role of
 - a)** alternating electric fields
 - b)** fixed flux density.
- 14** Charged particles move at constant speed as they travel around a single dee. These particles are also accelerating. Explain how these two statements can both be true.
- 15** Protons are accelerated in a cyclotron. If the voltage supply alternates at a frequency of 4 MHz, calculate the magnetic flux density required.

The mass of a proton is 1.67×10^{-27} kg.
- 16** Explain why identical particles with different energies can be accelerated in a cyclotron together.
- 17** Find an expression for the maximum kinetic energy for a proton in a cyclotron of radius R .

Practice questions

- 1 Charged particles enter a magnetic field of flux density T at right angles to the field. Which one of these would decrease the radius of the circular path of the charged particles?
 - A decrease in charge Q
 - B decrease in mass m
 - C increase in velocity v
 - D decrease in flux density B
- 2 A positively charged particle travels north at a steady speed, v . A magnetic field is applied in the horizontal plane in which the particle is travelling. The flux is directed from east to west. Which of the following describes the motion of the particle after it enters the field?
 - A The particle accelerates upwards in the vertical plane.
 - B The particle's motion is unchanged.
 - C The particle accelerates downwards in the vertical plane.
 - D The particle accelerates in the westerly direction.
- 3 An electron enters a uniform magnetic field, travelling at a steady speed at right angles to the field. The shape of the electron's path in the field is
 - A a circle
 - B a straight line
 - C a parabola
 - D an ellipse
- 4 The speed of an electron of charge e and mass m travelling in a circular path of radius r in a magnetic field B is given by
 - A $Bemr$
 - B $\frac{Bem}{2\pi r}$
 - C $\frac{mer}{B}$
 - D $\frac{Ber}{m}$
- 5 A 50 cm wire carries a current of 1.2 A. The force the wire experiences if it is placed in a flux density 0.3 mT is
 - A 0.18 N
 - B 1.8×10^{-4} N
 - C 18 N
 - D 0.018 N

- 6 A wire carrying a current is placed parallel to a magnetic field. When the wire is gradually turned so it is perpendicular to the field, the force experienced by the wire
- A stays at a constant value
 - B decreases to zero from a maximum value
 - C increases from zero to a maximum value
 - D remains zero
- 7 A magnetic field is from south to north. A current-carrying wire in the field experiences an upwards force. The direction of the current is
- A into the page
 - B from east to west
 - C from west to east
 - D downwards
- 8 When a proton in a cyclotron travels through a dee, which of these statements is true?
- A The proton is constantly accelerating and its speed is increasing.
 - B The proton travels at a constant speed and is not accelerating.
 - C The proton travels at a constant velocity and is constantly accelerating.
 - D The proton travels at a constant speed but is constantly accelerating.
- 9 The magnetic field of a cyclotron is
- A constant in magnitude and applied perpendicular to the plane of the dees
 - B varying in magnitude and applied perpendicular to the plane of the dees
 - C constant in magnitude and applied parallel to the plane of the dees
 - D varying in magnitude and applied parallel to the plane of the dees
- 10 A beta particle travels from east to west across a magnetic field of strength 0.6 mT , which is directed northwards. The beta particle travels at $4 \times 10^5 \text{ ms}^{-1}$. The force the beta particle experiences in the field is
- A $3.8 \times 10^{-14} \text{ N}$ downwards
 - B $3.8 \times 10^{-17} \text{ N}$ downwards
 - C $3.8 \times 10^{-14} \text{ N}$ upwards
 - D $3.8 \times 10^{-17} \text{ N}$ upwards
- 11 A current-carrying wire of length 10 cm is placed in a magnetic field as shown in Figure 7.21.
- a) Predict the direction of the force acting on the wire. (1)
 - b) Calculate the flux density if the force on the wire is 2 mN when the current is 0.4 A . (3)

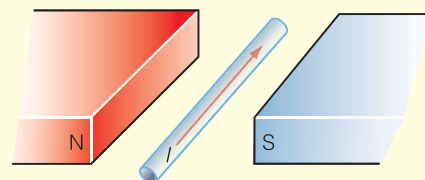


Figure 7.21

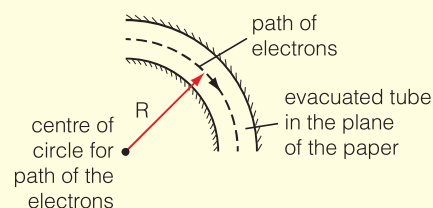
- c) A student wants to use the magnetic field to lift the wire up. The wire's mass per unit length is 0.5 g cm^{-1} . Calculate the minimum current required to allow this piece of wire to lift. (4)
- d) Explain why a larger current would be needed in reality. (1)
- e) Explain what happens if an alternating current is used instead. (4)

12 A hospital cyclotron uses magnetic fields to accelerate protons around a circular path. The diameter of the cyclotron is 2.0 m .

- a) If the field is in a suitable direction, the protons move in a circular path of constant radius. By referring to the force acting on the protons, explain how this happens. (4)
- b) Calculate the centripetal force acting on a proton when travelling around the cyclotron at a speed of $6 \times 10^7 \text{ m s}^{-1}$. (3)
- c) Calculate the flux density of the magnetic field needed to produce this force. (3)
- d) A cyclotron accelerates the protons to their final speed by applying a varying potential difference at the gaps between the two dees in which the protons travel. Explain how the potential difference is used to accelerate the protons. (4)

13 Electrons travel around a tube placed in a magnetic field of flux density 0.3 mT (see Figure 7.22).

- a) State and explain the direction of the magnetic field that forces the electrons to travel in this path. (2)
- b) If the radius of the orbit is 15 cm , calculate the flux density producing this motion. (4)
- c) Explain why the electrons are accelerating without speeding up. (2)
- d) Predict the approximate speed required for protons to travel in the same orbit in the same flux density. (3)



(2) **Figure 7.22**

- 14** An experiment is set up in which particles travel from left to right across a uniform magnetic field, directed into the plane of the page. The particles are travelling at the same speed. Describe in detail how their path through the magnetic field could be used to identify (8)
- a) the sign of the charge of electrons, protons, alpha particles and neutrons
- b) the relative masses of electrons, protons and alpha particles.

Stretch and challenge

- 15** A stream of charged particles is originally moving at velocity v and directed perpendicular to a uniform magnetic field. The particles follow a circular path in a plane perpendicular to the field and the original motion.
- a) Describe how this path changes if the magnetic field varies continuously, becoming weaker then stronger.

The Aurora Borealis is the appearance of coloured lights in the sky usually seen near the poles of the Earth. This is caused by charged particles that spiral along the Earth's magnetic field lines, and are channelled to the poles (Figure 7.23). As the particles interact with gases in the atmosphere, they cause coloured light with the emission of electron transitions.

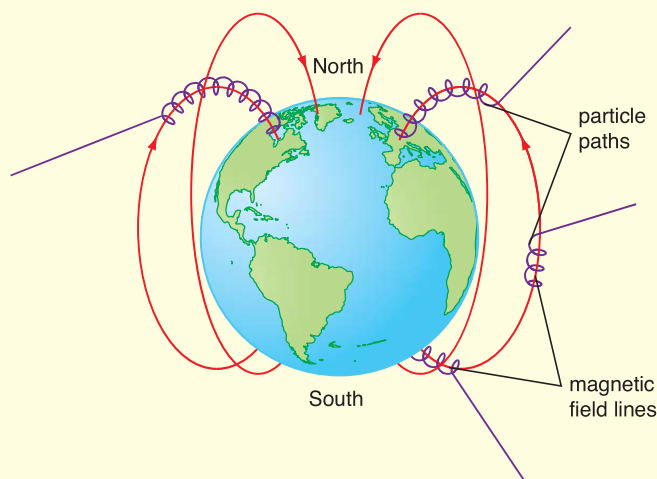


Figure 7.23

b) Describe how spiral motion is caused when a charged particle travels close to, but not quite parallel to a magnetic field line, by explaining:

- i)** what is meant by 'spiral motion'
- ii)** how the field affects components of velocity that are parallel and perpendicular to it
- iii)** how these components of velocity combine.

Use a diagram if this is helpful.

c) A charged particle is travelling at speed v at an angle θ to a magnetic field B .

- i)** State the components of velocity perpendicular and parallel to the field B .
- ii)** Calculate the radius of the spiral for a particle of charge Q , and the forward distance travelled while the particle circles the field once.
- iii)** Prove that these expressions are consistent with the expression $\tan \theta = \frac{2\pi r}{d}$.