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D. Fields / D.3 Motion in electromagnetic fields

The big picture

? Guiding question(s)

- How do charged particles move in magnetic fields?
- What can be deduced about the nature of a charged particle from observations of it moving in electric and magnetic fields?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Electromagnetic waves generated by natural and human-made sources can travel for long distances. They play a very important role in our daily lives. For example, radio waves are used in communications, radio and television broadcasting, cellular networks and indoor wireless systems.

Figure 1 shows a cell tower with antennas. Radio waves are created by controlling the motion of electrons within antennas. These waves interact with the electrons within a receiving antenna so the information carried by the radio waves is extracted by the receiving device.

The way in which particles interact with electromagnetic fields and electromagnetic waves deeply affects our lives.

Figure 1. The network of cellular communications works because we can detect (and control) the motion of electrons within antennas due to oscillations in an electromagnetic field.

Most of our understanding of the structure of matter was achieved by studying how different particles move through electric and magnetic fields.

How can the motion of a charged particle be used to understand its nature? How can understanding the nature of a particle be used to understand the behaviour of more complex structures, such as molecules?

International Mindedness

The search for understanding the fundamental structure of the Universe has shifted from being an individual quest carried out by individual scientists into a collaborative network of researchers around the world pushing the limits of our understanding of the Universe and of our technology.

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In 2022, Dr Maria Mironova (University of Oxford) was awarded the Atlas Thesis Award at CERN for her research on the Higgs boson (https://cds.cern.ch/record/2837159?ln=en (https://cds.cern.ch/record/2837159?ln=en)).

Every year, thousands of scientists from all over the world develop their research at the international research station CERN (https://www.home.cern/ (https://www.home.cern/)) to answer fundamental questions such as: What is the nature of our Universe? What is it made of? It is likely that many fundamental questions can only be answered and many problems solved by working collaboratively with a global perspective.

CERN brings nations together through science. It organises and sponsors international cooperation towards a better understanding of the fundamental structure of our Universe, promoting contacts between laboratories, institutes and scientists. Its success is in large part due to its rich international collaboration.

Prior learning

Before you study this subtopic make sure that you understand the following:

- Space, time and motion (see subtopics A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/), A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/), A.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/), A.4 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-43153/), A.5 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-45344/)).
- Electric and magnetic fields (see subtopic D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)).

D. Fields / D.3 Motion in electromagnetic fields

Motion of a charged particle in a uniform electric field

D.3.1: Motion of a charged particle in a uniform electric field

Learning outcomes

By the end of this section you should be able to:

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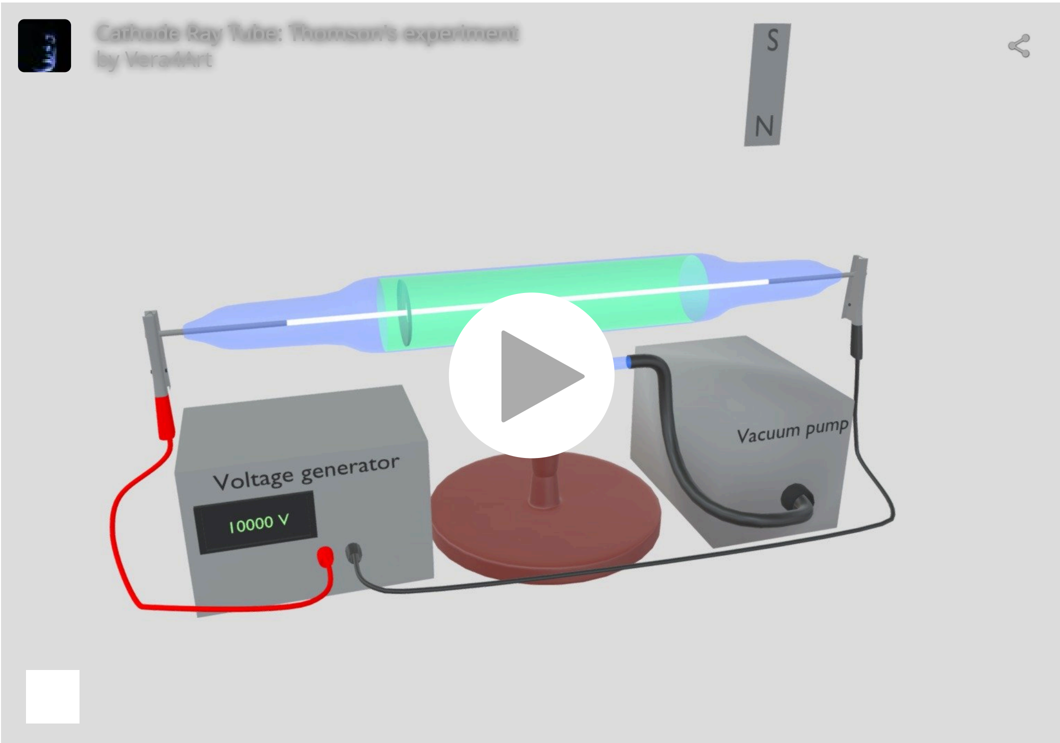
- Predict the direction of the force on a charged particle in an electric field, and calculate its magnitude.
- Understand that the acceleration of a charged particle in an electric field is affected by the magnitude (and direction) of the field and the charge and mass of the particle.
- Predict and calculate changes in the kinetic and electric potential energy of a charged particle that moves through an electric field.

How can we use electric fields to determine what a substance is made of?

The structure of the atom remained a mystery for many centuries. In 1897, Joseph John Thomson, Cavendish professor of Experimental Physics at Cambridge University, reported that negatively charged particles (which would later be named 'electrons') were detected travelling through a cathode ray tube. A cathode ray tube is a tube with a vacuum inside (**Interactive 1**). Beams of electrons (cathode rays) are fired through the vacuum and can be detected on a screen. By measuring how the path of these electrons was affected by an electric field, Thomson could determine fundamental properties of the electrons for the first time.



Interactive 1. A cathode ray tube similar to the one used in the discovery of the electron.

More information for interactive 1

The animation illustrates the working of a cathode ray tube (CRT) and how electric fields can be used to determine the fundamental properties of a substance.The simulation provides a dynamic environment where users can manipulate key parameters to better understand the relationship between electric forces, acceleration, and particle velocity.

Student view

When a charged particle enters a uniform electric field, it experiences a force that is directly proportional to its charge and the strength of the electric field. The force acting on the particle is described by the equation:

$$F = qE$$

Where:

- F is the force,
- q is the charge of the particle,
- E is the electric field strength.

This force causes the particle to accelerate, and the particle's acceleration is calculated using Newton's second law of motion:

$$a = \frac{F}{m}$$

Where:

- a is the acceleration,
- m is the mass of the particle.

A cathode ray tube is a vacuum-sealed glass tube equipped with metal electrodes at each end. When a high voltage is applied between these electrodes, the cathode (negative electrode) emits a stream of negatively charged particles known as cathode rays (later identified as electrons). These rays travel through the vacuum toward the anode (positive electrode). The electrons continue moving in a straight line unless acted upon by an external force.

In the simulation, users can modify the charge and mass of the particle, as well as the magnitude and direction of the electric field. This allows them to explore how these variables impact the acceleration, velocity, and path of the charged particle. For instance, positively charged particles accelerate in the direction of the electric field, while negatively charged particles move in the opposite direction. The simulation shows the resulting trajectory of the particle, which, when moving at right angles to the electric field lines, follows a parabolic path, similar to projectile motion in a gravitational field.

The interactive experience also demonstrates how the electric field influences the particle's energy. Users can track the particle's kinetic energy and electric potential energy as it moves through the electric field. By adjusting the electric field strength, users observe how the energy of the particle changes and understand how work is done by the electric field on the particle. The simulation provides real-time feedback, allowing users to calculate the energy transferred to the particle and explore concepts like work done by the electric field in a visual and hands-on manner.

For a more advanced exploration, the simulation allows users to experiment with non-uniform electric fields and observe the resulting changes in the particle's motion. By altering the electric field strength across different regions, users can observe how varying field strengths affect the particle's acceleration and trajectory. This feature helps users grasp the complexity of real-world electric fields that may not always be uniform.

The simulation also offers a step-by-step guide to solving related problems, allowing users to calculate acceleration, velocity, and the work done by the electric field using relevant equations. These calculations can be made using Newton's second law and the equation for electric force. By working through these tasks, users gain a deeper understanding of how electric forces affect the motion of charged particles and how to apply these principles to solve real-world problems.

The simulation is designed with accessibility in mind. It is fully screen reader compatible, and alternative text is provided for visual elements. The interface is also keyboard-navigable, ensuring that all users can interact with the simulation. Additionally, there is a text-based description of the key interactions between the electric field and the particle for those who require it.

In addition to an electric field, a magnetic field can also influence the motion of electrons in a cathode ray tube (CRT). When a magnetic field is applied perpendicular to the path of the electron beam, it exerts a force on the moving electrons due to the Lorentz force, causing them to follow a curved trajectory.

Overall, the Motion of a Charged Particle in a Uniform Electric Field simulation provides an engaging and interactive way to explore the fundamental principles of electromagnetism. By experimenting with different parameters, users can visualize and analyze the behavior of charged particles in electric fields, gaining valuable insights into the effects of electric forces on particle motion and energy transfer. This simulation is a powerful educational tool for understanding the dynamics of charged particles in electric fields and can be applied to solve problems involving kinetic energy, potential energy, and work done by the field.

Electric force on a charged particle

A charged particle in an electric field experiences a force that is described by the equation below (see section D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)):

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

This equation can be rearranged as:

$$F = qE$$

This equation can be used to calculate the magnitude (size) of the electric force acting on a charged particle given its charge and the magnitude of the electric field at the point where the particle is located.

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Assuming that the electric force is the only force acting on a charged particle, we can use Newton's second law $(F = ma)$ and combine the two equations into:

$$ma = qE$$

Thus we can calculate the acceleration experienced by a charged particle at a point in an electric field:

$$a = \frac{qE}{m}$$

If the particle is in the presence of a uniform electric field, the acceleration will be constant.

The motion of objects with uniform acceleration is covered in subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/). All of the ideas and equations in subtopic A.1 will be useful when describing the path of charged particles through uniform electric fields.

However, if a charged particle is placed in a non-uniform electric field, the equation for the acceleration is still valid and can be used to calculate the instantaneous acceleration (see subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)) experienced by the charged particle at that point in space.

Figure 1 shows a charged particle, Q, in a non-uniform electric field and a uniform electric field.

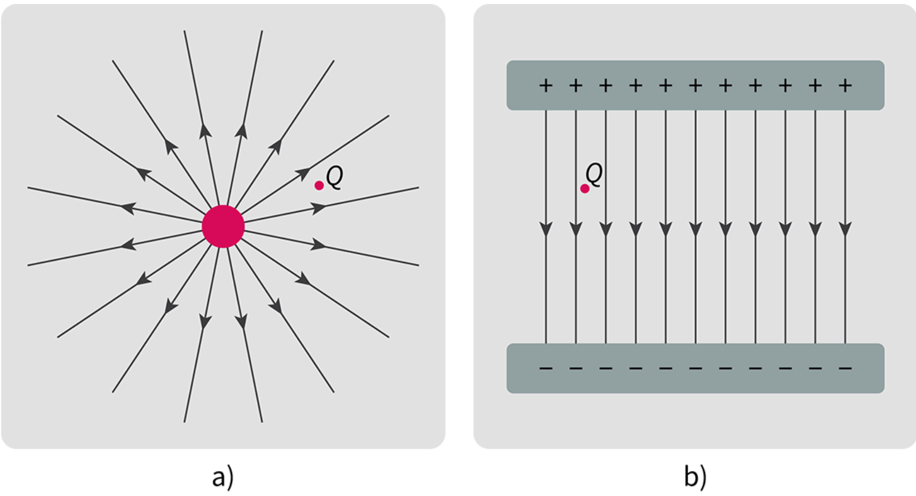

Figure 1. Charged particle, Q, in a non-uniform electric field and a uniform electric field.

More information for figure 1

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The image shows two sections illustrating a charged particle labeled "Q" in different electric fields. The left section depicts a non-uniform electric field, with arrows radiating outwards from a central point, demonstrating varying field strengths. The charged particle Q is placed near these arrows, depicting its interaction with the electric field. The right section illustrates a uniform electric field, characterized by parallel lines running vertically between two plates, one positively charged at the top and the other negatively charged at the bottom. The charged particle Q is positioned within these parallel lines, indicating a consistent force experienced throughout the field.

[Generated by AI]

When charged particle Q is placed in a non-uniform electric field, it experiences an acceleration that is different for every point in space. When charged particle Q is placed in a uniform electric field, it experiences a constant acceleration.

Unlike the force experienced by masses in a gravitational field (see subtopic D.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44096/)), which only depends on their mass, the acceleration experienced by charged particles in an electric field depends on both mass and charge.

There are two properties of a particle (charge and mass) that define the acceleration that it experiences in an electric field. Particles with identical charges experience different magnitudes of acceleration if their masses are different. Particles with identical masses experience different magnitudes of acceleration if their charges are different.

Motion of a charged particle in a uniform electric field

A charged particle in a uniform electric field experiences constant acceleration. The motion is similar to the motion covered in subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/). The difference is that the charge can be positive or negative. Positively charged particles experience an acceleration in the same direction as the direction of the electric field. Negatively charged particles experience an acceleration opposite to the direction of the electric field (**Figure 2**).

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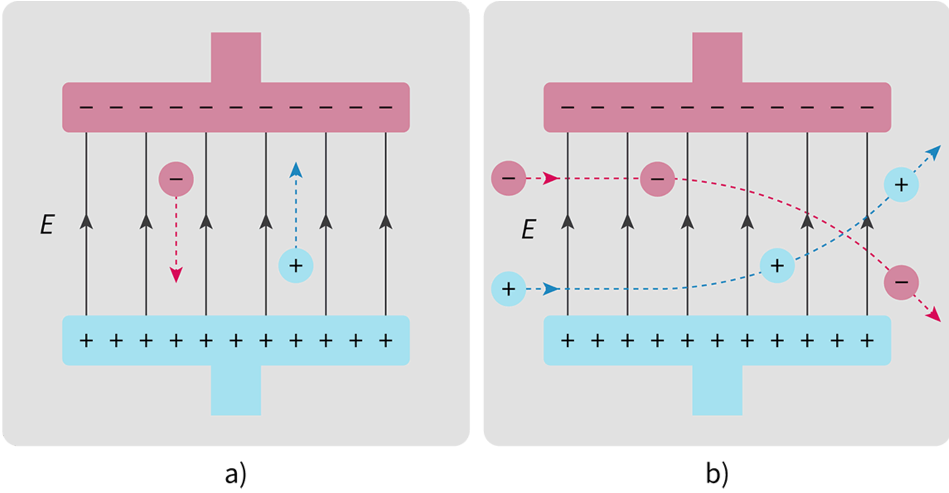

Figure 2. Motion of charged particles in a uniform electric field: a) charges initially stationary and b) charges initially moving horizontally across the field.

More information for figure 2

The diagram consists of two parts, both demonstrating how charged particles behave in a uniform electric field. In the left section, particles are initially stationary between two horizontal plates: the top plate is negative (indicated by dashes) and the bottom plate is positive (indicated by plus signs). The electric field is represented by downward arrows labeled 'E'. A negative charge is deflected downward and a positive charge upward. In the right section, particles initially move horizontally. The diagram depicts the negative charge curving downward and the positive charge upward as they pass through the field, indicating acceleration in directions respective to their charges.

[Generated by AI]

Figure 2 shows that negatively charged particles accelerate in the opposite direction to the direction of the electric field, E, while positively charged particles accelerate in the same direction as the electric field.

Since the acceleration is not affected by the particle's velocity, if the charged particles enter at right angles to the electric field lines, the resulting motion will follow the same rules as projectile motion in uniform gravitational fields (see subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)). The path will therefore be parabolic.

Use the simulation in **Interactive 2** to investigate how the magnitude and direction of the electric field, along with the charge and mass of a particle, affect the magnitude and the direction in which the particle accelerates.

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Interactive 2. Charged particle in a uniform electric field simulation.

More information for interactive 2

The interactive titled “Motion of a Charged Particle in a Uniform Electric Field” provides a visual and interactive way to understand the behavior of a charged particle when it is placed in a uniform electric field. This tool allows users to manipulate various parameters such as the particle’s charge, mass, and the strength of the electric field, and observe how these factors influence the particle's motion. The simulation demonstrates how the force acting on the particle is proportional to both its charge and the strength of the electric field.

When a charged particle enters the electric field, it experiences a force in the direction of the electric field if the particle is positively charged, or in the opposite direction if it is negatively charged. The force acting on the particle is given by the equation, $F = qE$, where F is the force, q is the charge of the particle, and E is the electric field strength. Using Newton’s second law, the acceleration of the particle is calculated by the equation:

$$a = \frac{F}{m}$$

$$\therefore a = \frac{qE}{m}$$

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Here a is the acceleration, m is the mass of the particle, and q and E are the charge and electric field strength, respectively.

The simulation consists of a charged particle placed in a uniform electric field, represented by parallel field lines. The direction of the electric field determines whether the force on the particle is positive or negative. Users can adjust sliders to modify different physical parameters and observe their effects on the particle's motion.

As users adjust the charge and mass of the particle, as well as the electric field strength, they can observe how these factors influence its motion. A stronger electric field exerts a greater force, leading to increased acceleration. A larger charge results in a stronger force. A positive charge moves with the field, while a negative charge moves against it. Heavier particles experience less acceleration because acceleration is inversely proportional to mass.

Reversing the electric field by moving the electric field slider downward flips the direction of force on all charges. Positive charges follow the field direction, while negative charges move against it. If a particle is already in motion, reversing the field can cause it to decelerate, stop, and then accelerate in the opposite direction.

This simulation serves as a valuable educational resource for understanding how charged particles interact with electric fields and how charge, mass, and field strength affect their motion. By offering an interactive experience, the tool reinforces theoretical concepts and enables users to visualize electromagnetism in action.

Drag and drop the words into the correct places in **Interactive 3** to check your understanding of the interactions between particles and fields.

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Drag the words into the correct boxes

Two properties of a particle define the strength of its interaction with electric and gravitational fields. The property that defines the magnitude of its force with an electric field is .
The property that defines the magnitude of its force with a gravitational field is .

For charged particles, the electric force acts in the same direction as the electric field.
For charged particles, the electric force is to the field.
For gravitational fields, the force experienced by a particle is always as the field.

electric charge | mass | positively | negatively | in the same direction | opposite

Check

Interactive 3. Electric and Gravitational Field Interactions.

Worked example 1

An electron is initially at rest in a uniform electric field. The magnitude of the field is 1.20×10^{-4} N C^{-1}. Determine:

1. the magnitude of the acceleration experienced by the electron
2. the speed of the electron after travelling 1 mm.

(Elementary charge, $e = 1.60 \times 10^{-19}$ C; electron rest mass, $m_e = 9.110 \times 10^{-31}$ kg)

1.

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$E = 1.20\times10^{-4}\ \mathrm{N\ C^{-1}}$ $e = q$ $= -1.60\times10^{-19}\ \mathrm{C}$ $m_\mathrm{e} = m$ $= 9.110\times10^{-31}\ \mathrm{kg}$
Step 2: Write out the equation.	$a = \dfrac{qE}{m}$
Step 3: Substitute the values given.	$= \dfrac{(1.60\times10^{-19}\times1.20\times10^{-4})}{9.110\times10^{-31}}$ You are calculating the magnitude of the acceleration, so you do not need to use the minus sign for the negative charge of the electron.
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 2.11\times10^{7}\ \mathrm{m\ s^{-2}}$ (3 s.f.)

2.

Solution steps	Calculations
Step 1: Identify the *suvat* equation required.	$v^2 = u^2 + 2as$
Step 2: Write out the values and convert the values to the units required for the equation.	$u = 0\ \mathrm{m\ s^{-1}}$ (electron starts from rest) $s = 1\ \mathrm{mm}$ $= 1\times10^{-3}\ \mathrm{m}$ (distance travelled) $a = 2.11\times10^{7}\ \mathrm{m\ s^{-2}}$
Step 3: Substitute the values given.	$v^2 = 0^2 + (2\times2.11\times10^{7}\times1\times10^{-3})$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$v = 205\ \mathrm{m\ s^{-1}}$ (3 s.f.)

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In **Worked example 1**, we used Newton's second law to determine the acceleration of an electron, initially at rest (not moving), in a uniform electric field.

If a positively charged particle is initially moving **against** an electric field, the particle experiences an acceleration that eventually brings it to rest and then increases its velocity in the opposite direction. This is the same as when a negatively charged particle is moving in the **same** direction as the electric field.

Imagine an object is thrown upwards from the surface of the Earth. The initial upwards velocity is in the opposite direction to the downwards gravitational field, so the speed of the object will decrease until the object reaches a maximum height and comes to rest. Then, as the object falls, its speed will increase in the direction of the gravitational field.

Study skills

A charged particle in a uniform electric field experiences a constant force, so its acceleration will also be constant. This means you can use the *suvat* equations to determine displacement, velocity and time.

Remember that displacement, velocity and acceleration are vectors (subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)), and their direction in space may require you to define them with a negative value.

Worked example 2

An electron between two oppositely charged plates, A and B, is moving from plate B towards plate A. The electric field strength between the plates is 1.50×10^3 N C^{-1}, and the distance between the plates is 2.00 mm. Determine how close the electron will get to plate A before coming to rest if the electron is initially moving at 8.6×10^5 m s^{-1}.

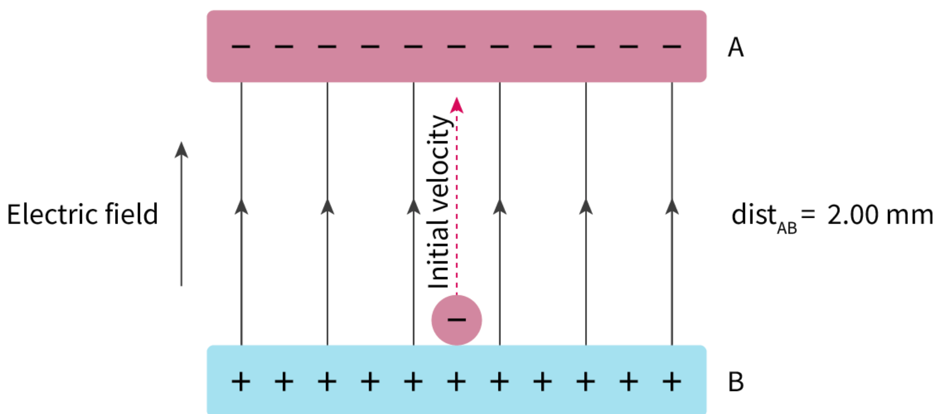

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Figure 3. An electron between oppositely charged plates.

More information for figure 3

The diagram illustrates an electron positioned between two oppositely charged plates labeled A and B. Plate A at the top is negatively charged, while plate B at the bottom is positively charged. The distance between the two plates is marked as 2.00 mm. Arrows pointing upward represent the direction of the electric field from plate B to plate A. The electron, depicted as a small circle with a negative sign, is moving with an initial velocity towards plate A. A dashed line indicates the path of the electron's initial velocity, moving from plate B upward towards plate A.

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(Elementary charge, $e = 1.60 \times 10^{-19}$ C; electron rest mass, $m_e = 9.110 \times 10^{-31}$ kg)

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$E = 1.50 \times 10^3 \text{ N C}^{-1}$ $e = q$ $= -1.60 \times 10^{-19} \text{ C}$ $m_e = m$ $= 9.110 \times 10^{-31} \text{ kg}$ $u = 8.6 \times 10^5 \text{ m s}^{-1}$ $v = 0 \text{ m s}^{-1}$ (electron comes to rest)

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Solution steps	Calculations
Step 2: Write out the equations and combine, then rearrange to find *s*.	$a = \frac{qE}{m}$ $v^2 = u^2 + 2as$ $v^2 = u^2 + 2\left(\frac{qE}{m}\right)s$ $s = -\left(\frac{u^2 m}{2qE}\right)$ When solving for s, there is a minus sign on the right-hand side of the equation. This is OK since the charge of the electron is negative. The displacement will have the same sign as the electric field strength.
Step 3: Substitute the values given.	$s = -\frac{[(8.6\times10^5)^2\times9.110\times10^{-31}]}{(2\times-1.60\times10^{-19}\times1.50\times10^3)}$ $= 1.40\times10^{-3}\text{ m}$ $= 1.40\text{ mm}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$\text{minimum distance to plate A} = 2.00 - 1.40$ $= 0.60\text{ mm (2 s.f.)}$

Creativity, activity, service

Strand: Activity
Learning outcome: Demonstrate engagement with issues of global significance

An electric discharge between the ground and the atmosphere causes a lightning strike. Each year, there are about 240 000 lightning strikes around the world, and about 2000 deaths.

Investigate the impact that lightning strikes have in your local community and in your country. Search for any negative effects that lightning strikes may have on animals and humans. Design a poster to raise awareness of what people can do in order to prevent accidents and what to do if caught in a lightning storm.

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We have looked at the motion of an electron moving with linear motion. This motion is described by having the velocity of the particle **parallel** to the direction of the electric field.

However, if the velocity of the particle has a component that is **perpendicular** (at right angles) to the electric field, the path of the particle is similar to the path of a projectile (subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)).

Worked example 3

A positively charged particle enters a region with a length of 10 mm where a uniform electric field is present. The particle is travelling at 5.10×10^5 m s^{-1}. It has a mass of 6.70×10^{-27} kg and a charge of $2e$. As the particle travels through the electric field, its path is deflected downwards.

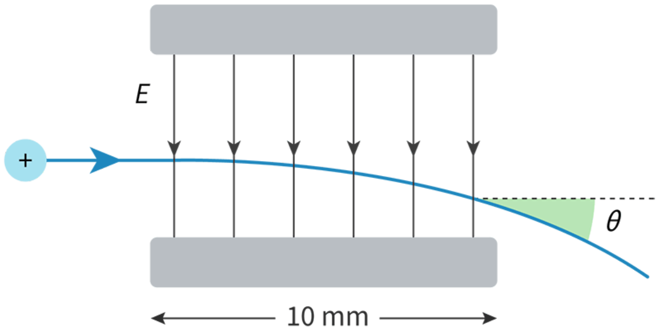

Figure 4. A positively charged particle in an electric field.

More information for figure 4

The diagram shows a positively charged particle entering a region with a uniform electric field. The particle's path is depicted as a series of diagonal arrows moving diagonally downward as it traverses through the field. The electric field is represented by parallel vertical lines that influence the path of the particle, causing it to deflect downward at an angle. The diagram illustrates the initial path of the particle as a horizontal line entering from the left, then bending downward within the electric field, and finally exiting with a deflected trajectory.

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After passing through the electric field, the path of the particle is at an angle θ to its original direction.

The magnitude of the electric field is 2.50×10^4 N C^{-1}. Assume the interaction with the gravitational field is negligible.

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1. State the direction of the electric field. Explain your answer.
2. Determine the magnitude of the force acting on the particle.
3. Determine the acceleration of the particle.
4. Calculate the time it takes the particle to pass through the electric field.
5. Show that as the particle exits the electric field, the vertical component of the velocity has a magnitude of about 2.34×10^4 m s^{-1}.
6. Determine the angle θ.

(Elementary charge, $e = 1.60 \times 10^{-19}$ C; electron rest mass, $m_e = 9.110 \times 10^{-31}$ kg)

$$m = 6.70 \times 10^{-27} \text{ kg}$$

$$\begin{aligned} q = 2e &= 2 \times 1.60 \times 10^{-19} \\ &= 3.20 \times 10^{-19} \text{ C} \end{aligned}$$

$$E = 2.50 \times 10^4 \text{ N C}^{-1}$$

$$\begin{aligned} s &= 10 \text{ mm} \\ &= 0.010 \text{ m} \end{aligned}$$

1. The path of the particle is deflected downwards, so there must be a force pushing the particle in that direction. Since the particle is positively charged, the electric field must also be pointing downwards, since positively charged particles experience a force parallel to the field.

2. $E = \dfrac{F}{q}$

$$\begin{aligned} F &= qE \\ &= 3.20 \times 10^{-19} \times 2.50 \times 10^4 \text{ N} \end{aligned}$$

$$F = 8.00 \times 10^{-15} \text{N (3 s.f.)}$$

3. $F = ma$

$$a = \frac{F}{m}$$

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$$a = \frac{8.00 \times 10^{-15}}{6.70 \times 10^{-27}}$$
$$= 1.19 \times 10^{12} \text{ m s}^{-2} \text{ (3 s.f.)}$$

4. The horizontal speed of the particle remains constant, so the horizontal component of the motion is uniform. Since there is no acceleration acting horizontally, the horizontal component of the velocity remains constant.

$$v = \frac{s}{t}$$

$$t = \frac{s}{v}$$
$$= \frac{0.010}{5.10 \times 10^5}$$
$$= 1.96 \times 10^{-8} \text{ s (3 s.f.)}$$

5. $u = 0 \text{ m s}^{-1}$ (initially, there is no vertical component of the velocity)

$$v = u + at$$
$$= 0 + (1.19 \times 10^{12} \times 1.96 \times 10^{-8})$$
$$= 23\,324 \text{ m s}^{-1}$$
$$= 2.33 \times 10^4 \text{ m s}^{-1} \text{ (3 s.f.)}$$

Since you are concerned with the magnitudes, you do not need to consider the downwards velocity as negative.

6. $\text{horizontal component of velocity} = 5.10 \times 10^5 \text{ m s}^{-1}$
$\text{vertical component of velocity} = 2.34 \times 10^4 \text{ m s}^{-1}$

$$\tan\theta = \frac{2.34 \times 10^4}{5.10 \times 10^5}$$

$$\theta = 2.63^\circ \text{ (3 s.f.)}$$

Worked example 4

An alpha particle is moving at 3.50×10^6 m s^{-1} in the opposite direction to an electric field with a strength of 1.25×10^4 N C^{-1}.

Calculate:

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1. the initial kinetic energy of the alpha particle, in joules and in electronvolts
2. the distance travelled by the particle before it comes to rest.

(Mass of alpha particle = 6.64×10^{-27} kg; charge of alpha particle = $2e$)

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units that can be used in equations.	$v = 3.50\times10^{6}\ \text{m s}^{-1}$ $E = 1.25\times10^{4}\ \text{N C}^{-1}$ $m = 6.64\times10^{-27}\ \text{kg}$ $q = 2e$ $= 2\times1.60\times10^{-19}$ $= 3.20\times10^{-19}\ \text{C}$
Step 2: Use the kinetic energy equation.	$E_{\text{k}} = \frac{1}{2}mv^{2}$ $= \frac{1}{2}\times6.64\times10^{-27}\times(3.50\times10^{6})^{2}$ $= 4.067 \times 10^{-14}\ \text{J}$ $= 4.07 \times 10^{-14}\ \text{J (3 s.f.)}$
Step 3: Convert the energy into electronvolts, using $1\text{eV} = 1.60 \times 10^{-19}\ \text{J}$.	$E_{\text{k}} \text{ in eV} = \frac{4.07 \times 10^{-14}}{1.60 \times 10^{-19}}$ $= 254\,000\ \text{eV}\ \ \text{(3 s.f.)}$ (or 254 keV or 0.254 Me)

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Solution steps	Calculations
Step 4: Calculate the distance using the energy change in joules — there are two ways to do this.	**Method 1** — use the equation for work done: Change in kinetic energy = work done by field $\Delta E_{\mathrm{k}} = W$ $= Fs$ and $E = \frac{F}{q}$ for a particle of charge q in a field of strength E So: $s = \frac{\Delta E_{\mathrm{k}}}{F}$ $= \frac{\Delta E_{\mathrm{k}}}{qE}$ $= \frac{4.067 \times 10^{-14}}{3.20 \times 10^{-19} \times 1.25 \times 10^{4}}$ $= 10.2\ \mathrm{m}\ (3\ \mathrm{s.f.})$ **Method 2** — calculate the acceleration and use a suvat equation: $u = 3.50 \times 10^{6}\ \mathrm{m\ s^{-1}}$ $v = 0$ To find the acceleration, use: $a = \frac{F}{m}$ and $F = Eq$ so: $a = \frac{Eq}{m}$ $= \frac{1.25 \times 10^{4} \times 3.20 \times 10^{-19}}{6.64 \times 10^{-27}}$ $= 6.024 \times 10^{11}\ \mathrm{m\ s^{-1}}\ (4\ \mathrm{s.f.})$ Use $v^2 = u^2 + 2as$ (where v and a are in opposite directions and therefore have opposite signs) to calculate s:

Student view

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Solution steps	Calculations
	$s = \frac{v^2 - u^2}{2a}$ $= \frac{0 - (3.50 \times 10^6)^2}{2 \times -6.024 \times 10^{-27}}$ $= 10.2 \text{ m (3 s.f.)}$

Higher Level: Work done by an electric field on a charged particle

As shown in section A.3.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/conservation-of-energy-id-43085/), the work done by a force is equivalent to the transfer of energy. This implies that as a charged particle travels through an electric field, we should expect a transfer of energy to take place since the field exerts a force on the particle and that force has an effect on the motion of the particle.

When a particle falls to the ground near the surface of the Earth, its speed (and its kinetic energy) increases as it loses height due to the work done by its weight. In a similar way, a charged particle is accelerated by the electric force, which changes the kinetic energy of the particle.

If we assume that a charged particle moves through an electric field, ignoring the effects due to the interaction with the gravitational field, we can express this idea as:

$$\text{work done by the field} = \text{change in kinetic energy of the particle}$$

For a charged particle moving through an electric field, the work done by the electric field is given by (subtopic D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)):

$$W = q\Delta V_{\text{e}}$$

Student view

where q is the charge of the particle and ΔV_{e} is the potential difference through which the particle moves.

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Concept

The work done by an electric field on a charged particle is equal to the change in kinetic energy of the particle.

Worked example 5

A pair of parallel plates with a potential difference between them of 450 V are separated by 150 mm. An electron is released from rest from the negatively charged plate. As the electron reaches the positively charged plate, determine:

1. the work done by the electric field on the electron
2. the speed with which the electron reaches the positively charged plate.

(Elementary charge, $e = 1.60 \times 10^{-19}$ C; electron rest mass, $m_e = 9.110 \times 10^{-31}$ kg)

$$\begin{aligned} q &= e \\ &= 1.60\times10^{-19}\ \text{C} \end{aligned}$$

$$\Delta V_\text{e} = 450\ \text{V}$$

$$m = 9.110\times10^{-31}\ \text{kg}$$

1. $$\begin{aligned} W &= q\Delta V_\text{e} \\ &= 1.60 \times 10^{-19} \times 450 = 7.2 \times 10^{-17}\ \text{J (2 s.f.)} \end{aligned}$$

2. Since the electron starts from rest, all of the work done by the field is equivalent to the kinetic energy of the electron.

$$E_\text{k} = \frac{1}{2}mv^2$$

$$\begin{aligned} v &= \sqrt{\frac{2E_\text{k}}{m}} \\ &= \sqrt{\frac{2\times7.2\times10^{-17}}{9.110\times10^{-31}}} \end{aligned}$$

Student view

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$$v = 1.257 \times 10^{7}\ \text{m s}^{-1}$$
$$= 1.3 \times 10^{7}\ \text{m s}^{-1}\ (2\ \text{s.f.})$$

We can consider the parabolic motion of a charged particle in an electric field in a similar way to a mass in a gravitational field as seen in subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/).

In many ways, the nature of the interaction of a particle with a uniform gravitational field is similar to the interaction of a charged particle with a uniform electric field.

Use the following activity to check your understanding of gravitational fields and electric fields.

Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Create a table with two columns like **Table 1** below. In each column, write the symbols, units, possible paths of particles, equations for force, equations for potential energy, and any other relevant factors, for each field.

Table 1. Comparing gravitational and electric fields.

Gravitational field	Electric field

5 section questions

Student view

Question 1

SL HL Difficulty:

An electron is in an electric field with a strength of 1.80×10^3 N C^{-1}.

Which row in the table gives the correct values for the magnitude of the force and the magnitude of the acceleration?

	Force	Acceleration
A	2.88×10^{-16} N	3.16×10^{-48} m s^{-2}
B	2.88×10^{-16} N	3.16×10^{14} m s^{-2}
C	2.88×10^{-14} N	3.16×10^{14} m s^{-2}
D	2.88×10^{-14} N	3.16×10^{-48} m s^{-2}

1 B ✓

2 A

3 C

4 D

Explanation

$q = 1.6 \times 10^{-19}$ C

$m = 9.110 \times 10^{-31}$ kg

$E = 1.8 \times 10^3$ N C^{-1}

$$\begin{aligned} F &= qE \\ &= 1.6 \times 10^{-19} \times 1.8 \times 10^3 \\ &= 2.88 \times 10^{-16} \text{ N} \end{aligned}$$

$$\begin{aligned} a &= \frac{F}{m} \\ &= \frac{2.88 \times 10^{-16}}{9.110 \times 10^{-31}} \\ &= 3.16 \times 10^{14} \text{ m s}^{-2} \text{ (3 s.f.)} \end{aligned}$$

Student view

Question 2

SL HL Difficulty:

Overview
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If a 1 positively ✓ charged particle is released from rest in a uniform electric field, it will experience a 2 force ✓ that acts in the same direction as the field.

Two identical charges will accelerate differently depending on their masses. The greater the mass, the 3 smaller ✓ the acceleration.

Accepted answers and explanation

#1 positively
positive
+ve

#2 force
acceleration

#3 smaller
lower
less

General explanation

Positively charged particles experience an acceleration in the same direction as the direction of the electric field.

Particles with identical charges experience different magnitudes of acceleration if their masses are different. The greater the mass, the smaller the acceleration.

Question 3

SL HL Difficulty:

A proton is released from rest and is accelerated by a potential difference of 250 V. Which row in the table gives the kinetic energy and speed of the proton after moving through this potential difference?

	Kinetic energy	Speed
A	4.00×10^{-17} J	2.19×10^{5} m s $^{-1}$
B	4.18×10^{-19} J	1.26×10^{5} m s $^{-1}$
C	4.00×10^{-17} J	1.55×10^{5} m s $^{-1}$
D	4.18×10^{-19} J	3.72×10^{5} m s $^{-1}$

(mass of a proton = 1.673×10^{-27} kg)

Student view

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1 A ✓

2 B

3 C

4 D

Explanation

$q = 1.6 \times 10^{-19}$ C

$V = 250$ V

$m = 1.673 \times 10^{-27}$ kg

As the proton moves through a potential difference of 250 V, it experiences a change in potential energy:

$$\begin{aligned} \Delta E_p &= q\Delta V \\ &= 1.6 \times 10^{-19} \times 250 \\ &= 4.00 \times 10^{-17} \text{ J (3 s.f.)} \end{aligned}$$

All this energy is transferred to kinetic energy, so this is also the final kinetic energy of the proton.

$$E_k = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E_k}{m}}$$

$$v = \sqrt{\frac{2 \times 4.00 \times 10^{-17}}{1.673 \times 10^{-27}}}$$
$$= 2.19 \times 10^5 \text{ m s}^{-1} \text{ (3 s.f.)}$$

Question 4

SL HL Difficulty:

A positively charged particle with charge *q* and mass *m* is initially moving with speed *v* against the direction of a constant electric field with strength *E*. What is the maximum distance that the particle will travel before coming to rest?

1 $\frac{mv^2}{2qE}$ ✓

2 $\frac{qE}{mv^2}$

Student view

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3 $\frac{mv^2}{qE}$

4 $\frac{2qE}{mv^2}$

Explanation

Force acting on the particle:

$$F = qE$$

Acceleration is constant:

$$\begin{aligned} a &= \frac{F}{m} \\ &= \frac{qE}{m} \end{aligned}$$

This acceleration is opposite to the initial velocity:

$$v^2 = u^2 + 2as$$

Substitute 0 for v since the particle comes to rest, v for u since this is its initial speed, and $-\frac{qE}{m}$ for a since this is the acceleration:

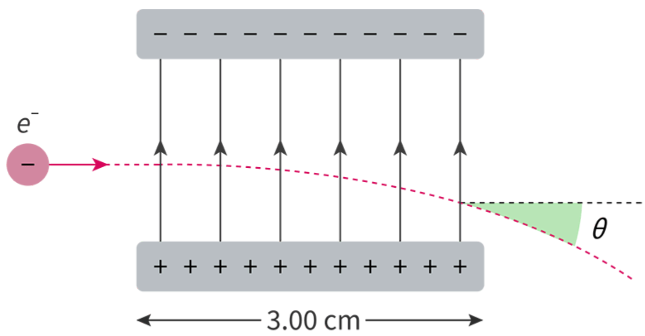
$$0^2 = v^2 + 2 \times \left(-\frac{qE}{m}\right) \times s$$

$$s = \frac{mv^2}{2qE}$$

Question 5

SL HL Difficulty:

An electron enters a region between two charged plates with an electric field of 1.30 kN C^{-1}. The electron is initially moving perpendicular to the electric field at 2.80×10^6 m s^{-1}. The electron passes a horizontal distance of 3.00 cm through the field.



More information

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Ignoring any edge effects, determine the angle at which the electron exits the electric field.

1 41.1° ✓

2 17.3°

3 23.1°

4 31.4°

Explanation

$q = 1.6\times10^{-19}\ \mathrm{C}$

$m = 9.110\times10^{-31}\ \mathrm{kg}$

$$\begin{aligned}E &= 1.30\ \mathrm{kN\ C^{-1}}\\ &= 1300\ \mathrm{N\ C^{-1}}\end{aligned}$$

$v = 2.80\times10^{6}\ \mathrm{m\ s^{-1}}$

$$\begin{aligned}s &= 3.00\ \mathrm{cm}\\ &= 0.03\ \mathrm{m}\end{aligned}$$

$$\begin{aligned}F &= qE\\ &= 1.60\times10^{-19}\times1300\\ &= 2.08\times10^{-16}\ \mathrm{N}\end{aligned}$$

$$\begin{aligned}a &= \frac{F}{m}\\ &= \frac{qE}{m}\\ &= \frac{2.08\times10^{-16}}{9.110\times10^{-31}}\\ &= 2.2832\times10^{14}\ \mathrm{m\ s^{-2}}\end{aligned}$$

The time it takes the electron to pass through the region is not affected by its acceleration. Horizontally, the electron moves at the same speed it entered the region. Therefore, the time taken to pass through the field is:

$$\begin{aligned}t &= \frac{\text{distance}}{\text{speed}}\\ &= \frac{0.030}{2.80\times10^{6}}\\ &= 1.07143\times10^{-8}\ \mathrm{s}\end{aligned}$$

During this time, the vertical component of the velocity increases from zero to:

$$\begin{aligned}v_{\text{vert}} &= a\times t\\ &= 2.2832\times10^{14}\times1.07143\times10^{-8}\end{aligned}$$

Student view

$$v_{\text{vert}} \simeq 2\,446\,291.36 \text{ m s}^{-1}$$

$$\begin{aligned}\tan\theta &= \frac{v_{\text{vert}}}{v_{\text{hor}}}\\ &= \frac{2\,446\,291.36}{2.80\times10^{6}}\end{aligned}$$

$$v = 41.1°(3 \text{ s.f.})$$

D. Fields / D.3 Motion in electromagnetic fields

Motion of a charged particle in a uniform magnetic field

D.3.2: Motion of a charged particle in a uniform magnetic field

D.3.3: Motion of a charged particle in perpendicularly orientated uniform electric and magnetic fields

Learning outcomes

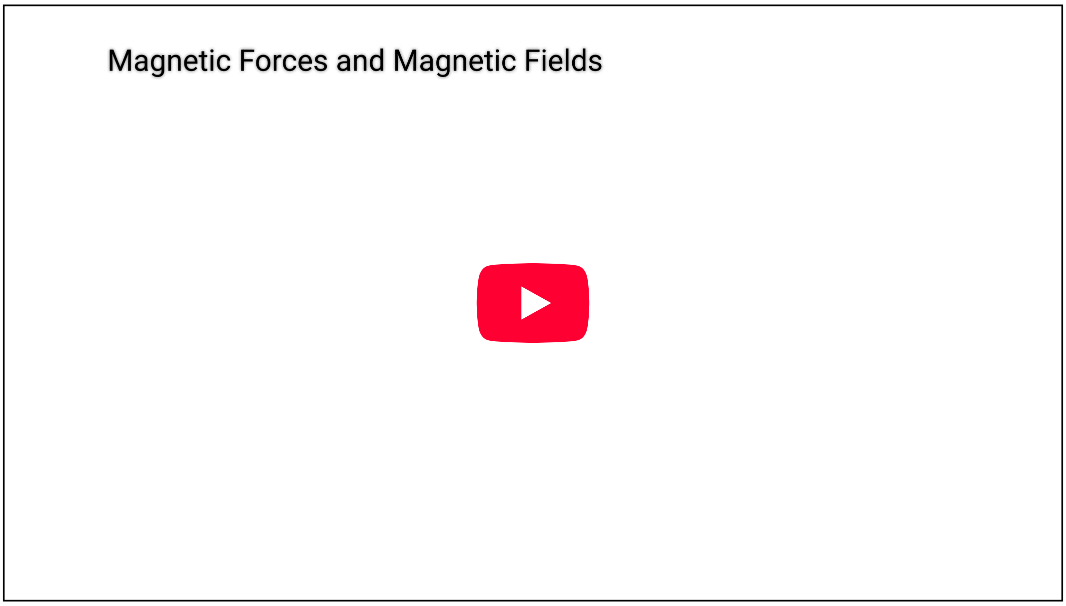
At the end of this section you should be able to:

- Describe the motion of a charged particle moving through a uniform magnetic field.
- Describe and explain the motion of a charged particle in magnetic and electric fields at right angles to each other.

The motion of charged particles is affected by the presence of an electric field, and magnetic materials are affected by a magnetic field. Electrons are not made of magnetic materials so will their motion be affected by a magnet? Watch **Video 1** to find out.

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/motion-of-a-charged-particle-in-a-uniform-id-45417/print/) Assign

Student view



Video 1. Are electrons affected by magnetic fields?

Magnetic force

Unlike the gravitational force and the electric force, where the direction of the force is defined by the direction of the field (and the sign of the charge), the magnetic force acts in different directions depending on the motion of the particle.

Use **Interactive 1** to investigate a charged particle entering a uniform magnetic field. Note that you can reverse the magnetic field direction by choosing a negative value on the magnetic field strength slider. You can also make the charge negative by moving the charge slider to the left.

Interactive 1. Motion of a charged particle in a magnetic field.

Overview
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More information for interactive 1

This interactive simulation titled “Motion of a Charged Particle in a Magnetic Field” visually represents the motion of a charged particle in a uniform magnetic field, allowing users to explore how various physical parameters mass, velocity, charge, and magnetic field strength affect the radius of the particle's circular path. The simulation is based on the Lorentz force, which governs the motion of charged particles in electromagnetic fields.

When a charged particle moves perpendicularly to a uniform magnetic field, it experiences a force that acts perpendicular to its velocity, causing it to move in a circular trajectory. The radius of this circular motion, r, is given by the equation.

The radius of the particle’s circular path is determined by the equation:

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

Here r is the radius of the circular motion, m is the mass of the particle, m is the velocity of the particle, q is the charge of the particle, and B is the magnetic field strength.

Set the initial values of velocity as 5×10^6 m/s, charge as 1×10^{-16} C and the magnetic field strength as 1 T as per the requirement of the surrounding data. Set the mass of the particle as 1×10^{-25} kg. Enable the "Show Radius" feature to display the radius of the circular path. The radius of the circular path followed by the positive charge is now displayed as 5mm.

Vary different parameters one at a time while keeping the others constant to observe patterns in the relationship between the radius and each variable. Now, vary the mass while keeping the other variables unchanged. The data is shown in the table below:

Mass	Radius
1×10^{-25} kg	5 mm
2×10^{-25} kg	10mm
3×10^{-25} kg	15 mm
4×10^{-25} kg	20mm

Users can observe that the radius increases as mass increases, showing a directly proportional relationship: $r \propto m$. Thus, heavier particles follow larger circular paths in a magnetic field.

Now vary the velocity by keeping other variables a constant. Users can now observe that the radius increases as velocity increases, confirming the proportionality: $r \propto v$.

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Thus, faster-moving particles have wider circular trajectories in a uniform magnetic field.

Now vary the charge by keeping other variables constant. Users can now observe that the radius decreases as charge increases, confirming the inverse relationship:

$$r \propto \frac{1}{B}$$

Thus, a stronger magnetic field bends the particle's path more sharply, resulting in a smaller circular motion.

From this interactive user can infer that charged particles always move in circles in a uniform magnetic field if the velocity is perpendicular to the field. Increasing the mass or velocity results in a larger radius of motion. Increasing the charge or magnetic field strength results in a smaller radius of motion. This behavior follows directly from the Lorentz force equation, confirming fundamental principles of electromagnetism.

This simulation provides an interactive, visual approach to understanding how charged particles behave in magnetic fields, reinforcing both theoretical knowledge and mathematical relationships in physics.

As you explore the effects of changing the mass, charge, initial velocity, and field strength, answer the following questions:

- What type of motion does a charged particle have in a uniform magnetic field?
- How is the path of the particle affected if there is an increase in:
  - mass
  - speed
  - charge
  - magnetic field strength?
- How is the path of a positively charged particle different from the path of a negatively charged particle?

Concept

The magnitude of the **magnetic force** acting on a charged particle is proportional to the **speed** of the particle. If the particle is at rest, the magnitude of the force experienced by the particle is zero.

The right-hand slap rule for a moving charged particle in a magnetic field can be used to predict the direction of the magnetic force acting on a positively charged particle. Hold your hand flat, with your thumb at right angles to your fingers as shown in **Figure 1.**

Student view

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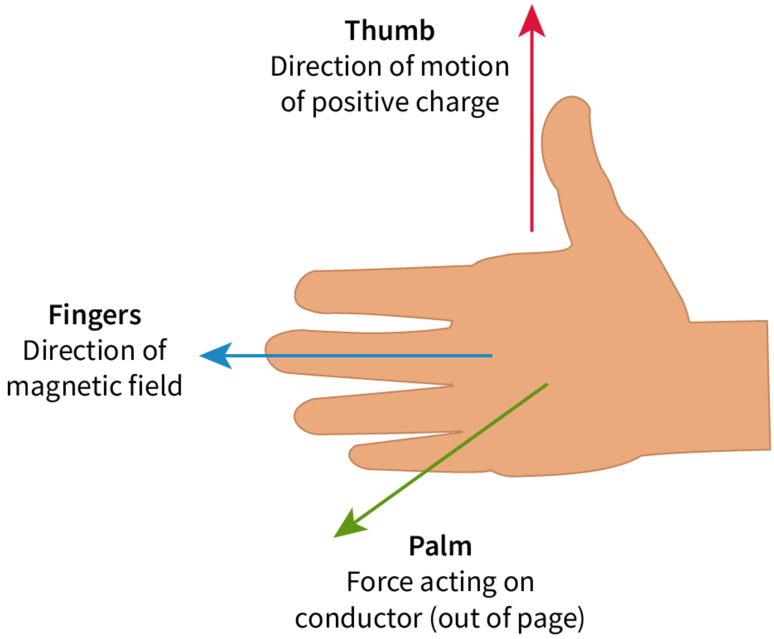

Figure 1. The right-hand slap rule showing the direction of the force on a current or moving charge in a magnetic field.

More information for figure 1

The illustration shows the right-hand slap rule. A hand is positioned with fingers pointing to the left, representing the direction of the magnetic field. The thumb points upwards, indicating the direction of motion of a positive charge. The palm faces out of the page, signifying the force acting on the conductor. This visual guide aids in understanding how to predict the direction of force using the orientation of the hand, thumb, and fingers.

[Generated by AI]

Point your **F**ingers in the direction of the **F**ield (another way to remember this is: there are many fingers and many field lines), and your thumbs in the direction of conventional current, then the direction of a slap with your palm is the direction of the outcome: the force.

Conventional current is the flow of positive charge, so if the particle is positively charged, the slap rule shows the direction of the force. If the particle is an electron or other negatively charged particle, the force acts opposite to the direction shown by the right-hand slap rule. (An alternative way to remember this is to use the right-hand slap rule for positive charges and a left-hand slap rule for negative charges.)

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Study skills

If you search for images or videos showing ways of remembering the direction of the force on moving charge in a magnetic field, you may find different versions, but they all give the same results.

One example is the left-hand rule shown in **Figure 2**.

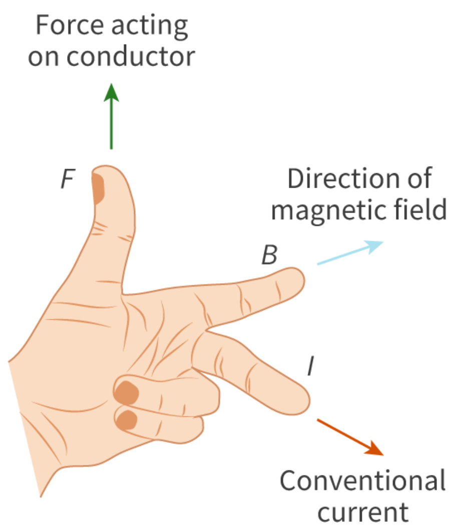

Figure 2. The left-hand rule showing the direction of the force on a current or moving charge in a magnetic field.

More information for figure 2

The image demonstrates the left-hand rule used to determine the direction of the force on a conductor in a magnetic field. It features a left hand with fingers positioned in specific directions. The thumb points upwards, representing the force acting on the conductor labeled 'F'. The index finger points to the right, indicating the direction of the magnetic field labeled 'B'. The middle finger points outward toward the viewer, symbolizing the direction of the conventional current labeled 'I'. This rule illustrates how the thumb, index, and middle fingers correspond to the force, magnetic field, and current directions, respectively.

[Generated by AI]

Since the magnetic force acting on a moving charged particle is always perpendicular (at right angles) to the velocity of the particle and the magnetic field, the interaction takes place in three-dimensional space. So we need a way to represent this interaction in a two-dimensional space.

Student
view

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Concept

Whenever we want to represent a vector (magnitude and direction) that is pointing ‘out of the page’ or ‘out of the screen’, we draw a circle with a point at its centre (like the tip of an arrow moving towards you).

To represent a vector that is pointing ‘into the page’ or ‘into the screen’, we draw a circle with an '×' (like the end of an arrow moving away from you).

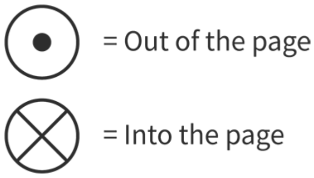

Figure 3. Symbols for ‘into the page’ and ‘out of the page’.

Study skills

Conventional current assumes that there are positively charged particles. The flow of electrons is opposite to conventional current. If it is not specified in a text, conventional current is assumed.

Exercise 1

Click a question to answer

It may be helpful to visualise what happens when certain conditions are altered or reversed.

Exercise 2

Click a question to answer

Student view

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Motion of a charged particle in a magnetic field

If a charged particle moves through a magnetic field with a velocity that has a non-zero component perpendicular to the field (see subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)), the particle experiences a force that is perpendicular to its velocity.

According to Newton's second law, the resultant force acting on an object is proportional to its acceleration.

So, for a charged particle moving through a magnetic field, its acceleration is perpendicular to its velocity. This is circular motion (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)). We will be using the concepts of circular motion to describe the path of a charged particle moving through a magnetic field.

Use the simulation in **Interactive 2** to investigate how different particles move in a magnetic field.

Interactive 2. How different charges move in a magnetic field.

More information for interactive 2

The interactive titled "How Different Charges Move in a Magnetic Field." simulation allows users to explore how charged particles move when subjected to a uniform magnetic field. The simulation visually demonstrates the effects of the Lorentz force, which causes charged particles to move in curved paths when subjected to a magnetic field.

Student view

When a charged particle enters a magnetic field, it experiences a force known as the Lorentz force. This force is always perpendicular to both the velocity of the particle and the magnetic field, causing the particle to move in a circular path. The magnitude of the magnetic force is given by the equation:

$$F = q(\vec{v} \times \vec{B})$$

Here F is the magnetic force, q is the charge of the particle, v is the velocity of the particle, and B is the magnetic field strength. Since the force is always perpendicular to the particle's velocity, it does no work on the particle. As a result, the particle's speed remains constant while only its direction changes. This results in a circular motion or a helical trajectory if the velocity has a component along the direction of the magnetic field.

The radius of the particle's circular path is determined by the equation:

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

Here r is the radius of the circular motion, m is the mass of the particle, m is the velocity of the particle, q is the charge of the particle, and B is the magnetic field strength.

The direction of the magnetic force on a positively charged particle can be determined using the right-hand rule: point your thumb in the direction of the particle's velocity, your fingers in the direction of the magnetic field, and your palm will point in the direction of the force. For a negatively charged particle, the force will be in the opposite direction. This rule helps users predict the direction of the particle's motion as it curves in the magnetic field.

The particle follows a circular trajectory due to the constant perpendicular force. The radius of the circular path is determined by the charge, mass, velocity, and magnetic field strength, which remain fixed in this simulation. A positively charged particle moves in one direction, while a negatively charged particle moves in the opposite direction, following the right-hand rule and left-hand rule, respectively. Since magnetic forces do no work on the particle, its speed remains constant, with only its direction changing over time. The red and blue arrows represent the velocity of the positive and negative charges respectively. The green arrow indicates the direction of the Lorentz force acting on the charged particle.

This simulation effectively illustrates the motion of a charged particle in a magnetic field without the need for parameter adjustments. By observing the circular motion of the particle, users can develop a better understanding of Lorentz forces, charge-dependent motion, and real-world applications in electromagnetism.

Drag the terms into the correct places in **Interactive 3** to describe what is happening to the particles in **Interactive 2**.

Overview
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Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. Interactive 2 shows two oppositely charged particles, which are initially moving .
2. The charged particle moves in an anticlockwise direction, while the charged particle moves in a clockwise direction.
3. Next to each particle, a vector is pointing towards the centre of the circle. This vector indicates the direction of the force and the of each particle.
4. According to the left-hand rule, the magnetic field is the page.

acceleration | negatively | upwards | into | positively

Check

Interactive 3. Drag and drop the words into the correct places.

There are several factors that affect the motion of a charged particle in a magnetic field. In a uniform magnetic field, a charged particle moves in a circle.

How is the radius of the circle affected by the magnetic field strength? How is the radius affected by the properties of the particle? In the following activity, you will explore these questions.

Activity

- **IB learner profile attribute:**
  - Thinker
  - Inquirer
  - Communicator
- **Approaches to learning:**
  - Thinking skills — Applying key ideas and facts in new contexts
  - Research skills — Using search engines and libraries effectively
  - Communication skills — Clearly communicating complex ideas in response to open-ended questions
- **Time required to complete activity:** 20 minutes

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- **Activity type:** Group activity

When a charged particle enters a magnetic field, as it moves through the magnetic field lines, its path is deflected by a force that is perpendicular to the velocity of the particle. This causes the particle to move in a circle. The radius of that circle is defined by some of the following variables: mass, charge, speed, kinetic energy, magnetic field strength.

1. Discuss how each of these variables might affect the radius.
2. Identify which variables produce bigger radiuses if they are increased, which variables produce smaller radiuses if they are increased, and which variables have no effect on the radius.
3. Research the basic principles of a bubble chamber and how the tracks left by particles are used to determine the properties of the particles.

Write a short summary of how the variables affect the radius of the path of a particle inside a magnetic field, then explain how a bubble chamber is used to determine different properties of particles.

Work done by a uniform magnetic field on a charged particle

The centripetal force acting on a charged particle moving in a magnetic field is perpendicular to the velocity (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)). There is no component of the force acting in the same direction as the velocity, and thus no work is done on the particle.

In the absence of other external forces, the kinetic energy of a particle that moves along a circular path in a magnetic field remains constant. A particle experiences no energy changes while travelling through a uniform magnetic field.

The momentum (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)) will not be constant, since momentum is a vector and the direction of the velocity is constantly changing.

Table 1 summarises the motion of a particle in a uniform magnetic field where there are no other forces.

Student
view

Table 1. Motion of a particle in a uniform magnetic field

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Quantity	Description
Speed	constant
Kinetic energy	constant
Velocity	constantly changing in direction
Momentum	constantly changing in direction
Magnitude of momentum	constant
Radius of path	constant

Concept

For a charged particle that moves through a uniform magnetic field:

- The work done by the magnetic field on the particle is zero.
- The kinetic energy of the particle, its speed and the radius of its path are constant.

Motion of a charged particle in perpendicular electric and magnetic fields

Is it possible to have a situation in which a particle is acted on by an electric force and a magnetic force so that the two forces are balanced? What would the path of a particle be?

For the forces to be balanced, the electric force and the magnetic force need to have the same magnitude and act in opposite directions. In this case, the path of the particle will be linear, and it will move with constant velocity.

Figure 4 shows a positively charged particle moving through perpendicular electric and magnetic fields in such a way that the electric and magnetic forces are opposed. The direction of the electric field is downwards and so is the electric force. The direction of the magnetic field is into the screen so, according to the left-hand rule, the magnetic force is acting upwards, opposite to the electric force.

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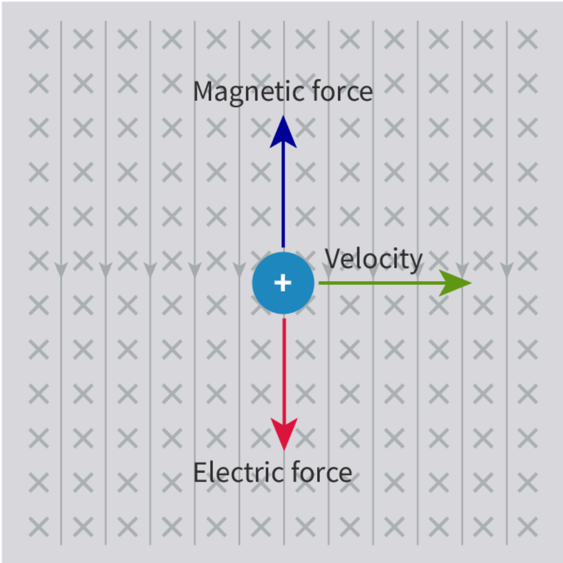

Figure 4. A positively charged particle moving through perpendicular electric and magnetic fields.

More information for figure 4

The diagram illustrates a positively charged particle (denoted by a "+" in a blue circle) moving through perpendicular electric and magnetic fields. The background consists of a grid of 'X' symbols, indicating the direction of the magnetic field is into the screen. The particle has three labeled vectors: 'Velocity' pointing to the right (green arrow), 'Magnetic force' pointing upward (blue arrow), and 'Electric force' pointing downward (red arrow). These forces create a crossed vector effect overlaid on the particle, showing the different directional influences on its movement.

[Generated by AI]

Worked example 1

A negatively charged particle enters a region where uniform electric and magnetic fields are present. The particle is moving with constant velocity. The directions for the velocity of the particle and the electric field are shown in the diagram. Identify the direction of the magnetic field. Justify your answer.

Student
view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

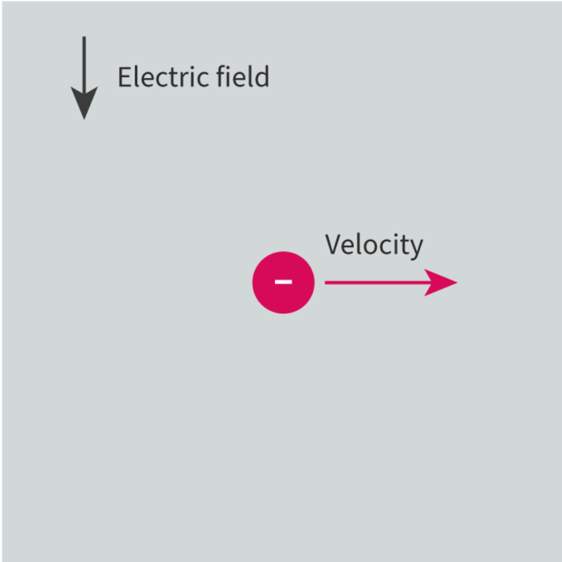

Figure 5. A negatively charged particle in uniform electric and magnetic fields.

More information for figure 5

The image is a diagram illustrating a negatively charged particle, represented by a circle with a negative sign inside. To the right of the circle, there is an arrow labeled 'Velocity' pointing horizontally to the right, indicating the direction of movement. Above the circle, there is a downward arrow labeled 'Electric field,' showing the direction of the uniform electric field. This setup is commonly used in physics to depict the motion of particles in electric and magnetic fields, and the diagram helps visualize the forces acting on the particle.

[Generated by AI]

The electric field is acting downwards, and the charge is negative, so the electric force acting on the particle has an upwards direction.

The particle is moving with constant velocity, so it is not accelerating. Therefore, there must be a magnetic force cancelling the electric force.

The magnetic force is equal in magnitude and opposite in direction to the electric force.

Using the right-hand slap rule but reversing the direction of the answer (because the charge is negative), the magnetic field is acting into the page. (Alternatively, use the left-hand slap rule for a negative charge.)

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Using the resultant effect on the particle and one known field direction enables you to deduce the direction of the other field.

Worked example 2

A positively charged particle enters a region where uniform electric and magnetic fields are present. The particle is moving with constant velocity. The directions for the velocity of the particle and the magnetic field are shown in the diagram. Identify the direction of the electric field. Justify your answer.

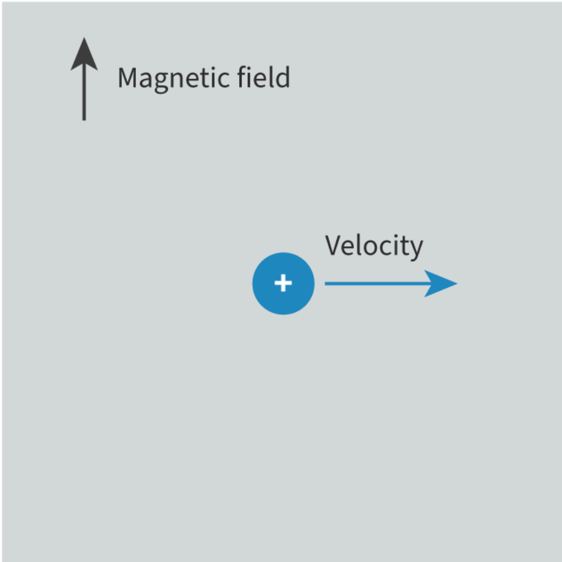

Figure 6. A positively charged particle in uniform electric and magnetic fields.

More information for figure 6

The diagram illustrates a positively charged particle represented by a blue circle with a plus sign. The particle is moving to the right, as indicated by a rightward arrow labeled "Velocity." Besides the velocity vector, there's an upward arrow positioned to the left of the particle, labeled "Magnetic field." This indicates the vertical direction of the magnetic field in the region. The focus of the diagram is to determine the direction of the electric field, considering the given vectors for the velocity of the particle and the magnetic field. The electric field direction needs to be deduced based on this information.

[Generated by AI]

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According to the right-hand slap rule, there is a magnetic force acting on the (positively) charged particle that is directed out of the page.

Since the particle is moving with constant velocity, it is experiencing no acceleration, which can only occur if the forces are balanced. It must be experiencing an electric force acting in the opposite direction to the magnetic force – into the page.

All positive charges will experience an electric force acting parallel to the field, so the electric field must be into the page.

Aspect: Models

How are the concepts of energy, forces and fields used to determine the size of an atom?

During the 1880s and 1890s, scientists investigated cathode rays (see subtopic D.3.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/motion-of-a-charged-particle-in-a-uniform-id-45417/)). This led to the discovery of the electron by J.J. Thomson in 1899. The idea of an indivisible atom was challenged for the first time in more than 2000 years, and a new model for the atom was developed. A few decades later, the proton was discovered by Ernest Rutherford (https://en.wikipedia.org/wiki/Ernest_Rutherford), and one decade after that, Sir James Cavendish discovered the neutron.

It seemed that the structure of matter had been revealed, and how fields interacted with matter could explain the behaviour of the particles in the atom. However, these concepts could not explain experiments that were performed during the first half of the 20th century, and a different branch of physics (quantum physics) was developed to explain the observations. Many years passed, and the theories about the structure of the atom evolved into the model we have today.

Will the models used to describe the underlying structure of the Universe ever stop evolving? If they will, does that mean that we will have a complete understanding of the structure of the Universe? Are there aspects of how the Universe is structured that we will never know?

Use the activity to check your understanding of the motion of a charged particle in electric and magnetic fields.

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Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Look at the simulation in **Interactive 4.** Predict the direction of the force that will act on the particle according to:

- its charge
- the direction of the field
- the nature of the field (electric or magnetic)
- its velocity.

After predicting the direction, click the 'Show answer' button and check whether you were correct. Try to predict the direction of the force successfully 10 times.

Interactive 4. Predict the direction of the force on the particle.

More information for interactive 4

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The interactive simulation titled “Predict the Direction of the Force on the Particle” challenges users to apply their knowledge of electric and magnetic forces to predict the direction of the force acting on a charged particle. The tool allows users to explore how the charge of the particle, the type of field (electric or magnetic), the field direction, and the particle’s velocity determine the force’s direction. Users are encouraged to predict the force direction before clicking the "Show Answer" button to check their accuracy. By attempting this prediction at least 10 times, users develop a deeper understanding of the fundamental principles of electromagnetism and the rules governing force interactions.

The simulation is based on the following physical laws:

A. Electric Forces (Coulomb’s Law)

A charged particle in an electric field experiences a force given by:

$$F = qE$$

Here, F is the force, E is the electric field strength, and q is the charge of the particle.

A positively charged particle moves in the direction of the electric field. A negatively charged particle moves opposite to the electric field. The force remains constant in direction and magnitude if E is uniform.

B. Magnetic Forces (Lorentz Force Law)

A charged particle in a magnetic field experiences a force given by:

$$F = q(\vec{v} \times \vec{B})$$

Here F is the magnetic force, q is the charge of the particle, v is the velocity of the particle, and B is the magnetic field strength. The magnetic force is the cross product of the velocity vector and magnetic field vector, meaning the force is always perpendicular to both the velocity and the field. For a positive charge in a perpendicular magnetic field, the right-hand rule can be applied. For that, point your right-hand fingers in the direction of $\vec{v}$, curl them toward $\vec{B}$, then your thumb points in the direction of the force. For negative charges, the force direction is reversed. The force causes circular or helical motion without changing the particle’s speed.

Through this interactive, users are shown a charged particle moving in an electric or magnetic field. The type of field, its direction, and the charge of the particle are provided. Users must predict the force direction based on these parameters.

By engaging with this interactive tool, users will develop intuition for how electric and magnetic fields affect charged particles, strengthen their understanding of the right-hand rule for magnetic force predictions, reinforce key electromagnetism concepts through active learning and repetition, gain experience in distinguishing between the effects of electric and magnetic fields on motion.

5 section questions

Student view

Question 1

SL HL Difficulty:

A positively charged particle enters a magnetic field with a velocity that is perpendicular to the field. The particle moves along a circular path in an anticlockwise direction. Which of the following changes will result in the particle moving in a **clockwise** direction?

1. Use a negative charge instead of a positive charge.
2. Reverse the direction of the magnetic field.
3. Reverse the direction the particle is moving in when it enters the field.

1 1 and 2 ✓

2 1 only

3 2 only

4 1 and 3

Explanation

If there is a negative charge instead of a positive charge, the force will act in the opposite direction, causing the particle to move clockwise.

The same is true for the direction of the field. This is a vector and, according to the left-hand rule, if reversed, then the force will act in the opposite direction, causing the particle to move in a clockwise direction.

The direction the particle is moving in has no impact, as, although a vector, changing the direction of the force only means it will go anti-clockwise in the opposite y-axis direction. It will not make it move in the opposite circular direction.

Question 2 SL HL Difficulty:

An electron is moving between two parallel charged plates, where perpendicular electric and magnetic fields are present. The motion of the electron does not change.

More information

What is the direction of the magnetic field?

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1 Out of the screen ✓

2 Into the screen

3 Upwards

4 Downwards

Explanation

The constant motion of the electron means that the resultant force must be zero. The direction of the electric field between the plates is upwards, so the electric force is downwards. Since the direction of the electric force is downwards, the direction of the magnetic force is upwards. According to the left-hand rule, this corresponds to a magnetic field acting out of the screen.

Question 3

SL HL Difficulty:

If a charged particle is moving perpendicular to a magnetic field, it will experience a force that is perpendicular to the field and the 1 velocity ✓ of the particle. The total work done by the magnetic field on the particle is always 2 zero ✓ , which means that the 3 kinetic energy ✓ of the particle is constant.

Accepted answers and explanation

#1 velocity
movement
motion

#2 zero
0

#3 kinetic energy
speed

General explanation

The magnetic force acting on a charged particle is always perpendicular to its velocity. Since there is no force acting in the direction of motion, no work is done by the magnetic field on the particle. Since the particle has a fixed amount of energy while moving through the field, its kinetic energy is constant.

Student
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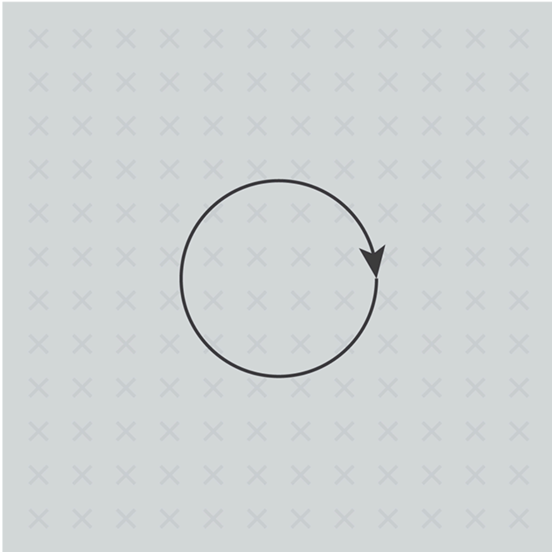
Question 4

SL HL Difficulty:

A charged particle follows a circular path in a uniform field. The direction of the field is into the screen, and the particle is moving in a clockwise direction.



More information

Which statement correctly describes the nature of the field and the charge?

1 A negative charge moving in a magnetic field ✓

2 A positive charge moving in a magnetic field

3 A negative charge moving in an electric field

4 A positive charge moving in an electric field

Explanation

The field is a magnetic field since this is the only field in which charged particles move in a circle. At any point along the circle, if the left first finger is pointing into the screen, and the second finger is pointing in the direction of the velocity (at a tangent to the circle), the thumb will be pointing away from the centre of the circle. Since the force is actually pointing towards the centre of the circle, the conventional current must be flowing anticlockwise, so the particle is negatively charged.

Question 5

SL HL Difficulty:

An electron is moving away from a current-carrying wire. By analysing the direction of the magnetic field created by the wire at the point where the electron is, determine the direction of the magnetic force acting on the electron.

Student view

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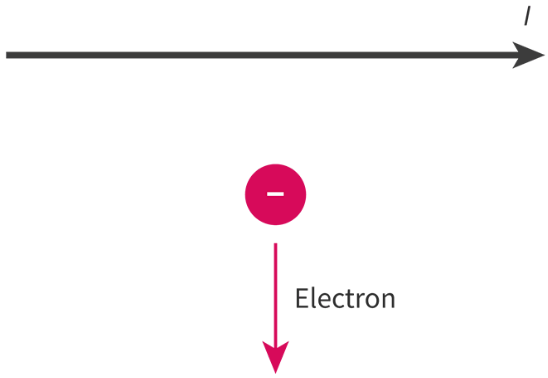


More information

1 The force is acting towards the left ✓

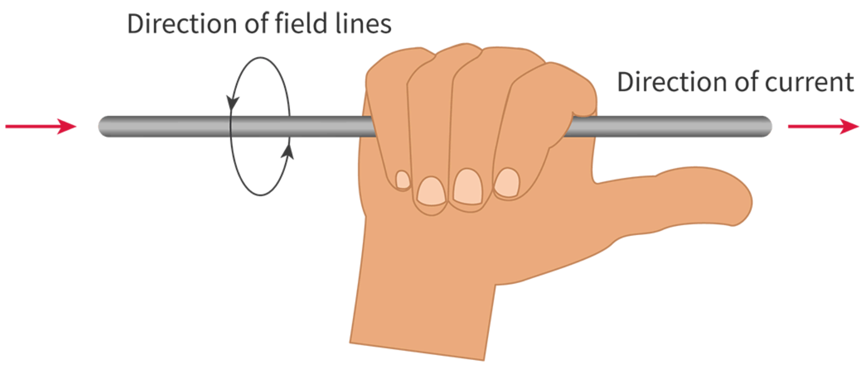
2 The force is acting towards the right

3 The force is acting into the screen

4 The force is acting out of the screen

Explanation

According to the right-hand rule for the magnetic field produced by a current-carrying wire, the magnetic field at the position of the electron is pointing into the screen.



More information

According to the left-hand rule for charges moving in a magnetic field, this will produce a force that is acting to the right. However, for an electron that's moving downwards, the conventional current is going upwards, so the force is acting towards the left.

D. Fields / D.3 Motion in electromagnetic fields

Magnitude of the magnetic force

Student view

D.3.4: Magnitude and direction of the force on a charge moving in a magnetic field

Overview
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Learning outcomes

By the end of this section you should be able to:

- Predict the radius of the circular path followed by a charged particle moving through a uniform magnetic field.
- Describe how the path of a charged particle moving through a magnetic field can be used to determine the properties of the particle.
- Predict the direction of the force on a charged particle in a magnetic field, describe the path taken by the particle and use the equation:

$$F = qvB\sin\theta$$

Figure 1 shows particle tracks that were formed in CERN's first liquid hydrogen bubble chamber to be used in experiments. By studying the paths of particles passing through the bubble chamber, scientists discovered the properties of some of the fundamental particles of matter.

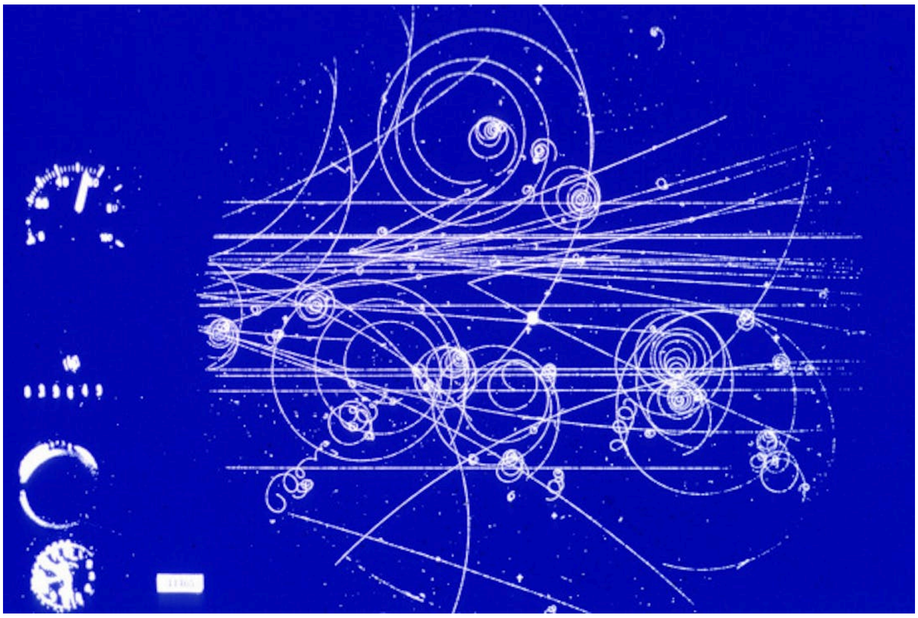

Figure 1. Particle tracks in CERN's first liquid hydrogen bubble chamber.

More information for figure 1

Student view

Overview
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The image displays particle tracks from CERN's first liquid hydrogen bubble chamber. Swirling lines of different sizes and lengths crisscross the blue background, creating a complex web of spirals and curves. The paths often intersect and loop, highlighting the motion of charged particles in a magnetic field. These visible tracks help scientists study particle behavior to understand fundamental properties of matter. The background appears dotted with smaller points, possibly representing neutral particles or background noise.

[Generated by AI]

We have looked at the interaction between a moving charged particle and a magnetic field in terms of the magnetic force (see subtopic D.3.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/motion-of-a-charged-particle-in-a-uniform-2-id-45418/)). This force always acts perpendicular to the velocity of the particle, which causes the particle to move in circles when placed in a uniform magnetic field. How can the magnitude of the force acting on a charged particle in a uniform magnetic field be determined?

Force on a charged particle moving in a magnetic field

The magnetic force experienced by a charged particle moving through a magnetic field is affected by the direction in which the particle is moving. For a particle moving parallel to the field, the force is zero. The magnitude of the force is greatest when the particle is moving perpendicular to the field.

For a particle that moves with a velocity that forms an angle θ to the direction of the field, the components of the velocity need to be considered (see subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)).

Figure 2 shows a particle q moving at an angle θ to the magnetic field. The component of the velocity that is perpendicular to the field is given by $v \sin\,\theta$. It is the magnitude of this component that defines what the magnitude of the force will be, along with the magnetic field strength and the charge of the particle.

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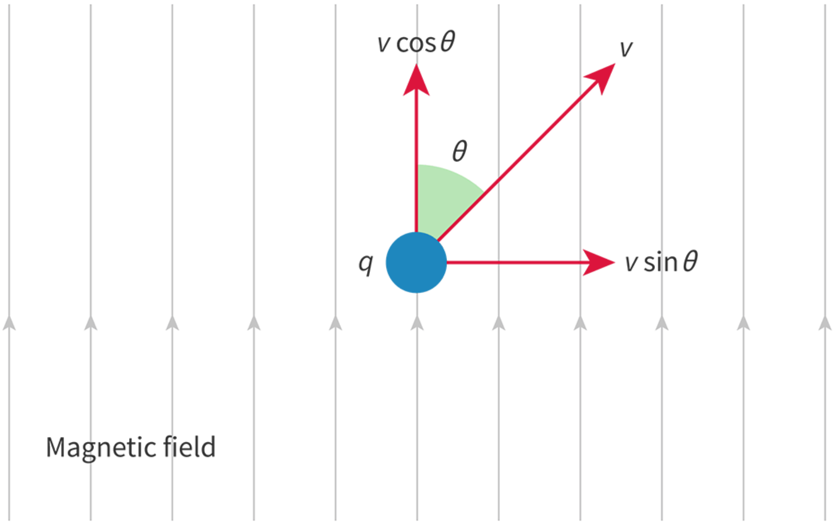

Figure 2. A particle moving at an angle to a magnetic field.

More information for figure 2

The diagram illustrates a particle labeled 'q' moving through a magnetic field at an angle 'θ'. The magnetic field is depicted as arrow lines directed into the page and is indicated by the symbol 'B'. The particle's velocity vector is shown with components broken into 'vcosθ' and 'vsinθ', with 'vsinθ' being perpendicular to the magnetic field. This perpendicular component determines the magnitude of the magnetic force on the particle. The diagram uses color coding to differentiate various vector components, with symbols and labels clearly presented to visualize the relationships between the angle, velocity components, and magnetic field orientation. Arrows signify the direction of forces and velocities involved.

[Generated by AI]

The equation for the force on a charge moving in a magnetic field is shown in **Table 1**.

Table 1. Equation for the force on a charge moving in a magnetic field.

Student
view

Overview
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Equation	Symbols	Units
$F = qvB\sin\theta$	F = force	newtons (N)
	q = charge	coulombs (C)
	v = velocity	metres per second (m s^{-1})
	B = magnetic field strength	teslas (T)
	θ = angle between velocity and field	degrees (°)

Exercise 1

Click a question to answer

Study skills

Whenever you are using trigonometric functions (sine, cosine and tangent) on your calculator, be careful to set up the angle to 'RAD' or 'DEG' according to whether the values in the question are given in radians or degrees.

Charged particles in a uniform magnetic field move in circles. Use the activity to explore how the radius of the circle can be calculated.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Student view

Look at the simulation of the motion of a charged particle in a magnetic field in **Interactive 1.**

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Interactive 1. Motion of a charged particle in a magnetic field.
Credit: Tom Walsh

More information for interactive 1

This interactive simulation titled “Motion of a Charged Particle in a Magnetic Field” visually represents the motion of a charged particle in a uniform magnetic field, allowing users to explore how various physical parameters mass, velocity, charge, and magnetic field strength affect the radius of the particle's circular path. The simulation is based on the Lorentz force, which governs the motion of charged particles in electromagnetic fields.
When a charged particle moves perpendicularly to a uniform magnetic field, it experiences a force that acts perpendicular to its velocity, causing it to move in a circular trajectory. The radius of this circular motion, r, is given by the equation.
The radius of the particle’s circular path is determined by the equation:

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

Here r is the radius of the circular motion, m is the mass of the particle, m is the velocity of the particle, q is the charge of the particle, and B is the magnetic field strength.
Set the initial values of velocity as 5×10^6 m/s, charge as 1×10^{-16} C and the magnetic field strength as 1 T as per the requirement of the surrounding data. Set the mass of the particle as 1×10^{-25} kg. Enable the "Show Radius" feature to display the radius of the circular path. The radius of the circular path followed by the positive charge is now displayed as 5mm.
Vary different parameters one at a time while keeping the others constant to observe patterns in the relationship between the radius and each variable. Now, vary the mass while keeping the other variables unchanged. The data is shown in the table below:

Mass	Radius
1×10^{-25} kg	5 mm
2×10^{-25} kg	10 mm

Student
view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Mass	Radius
3×10^{-25} kg	15 mm
4×10^{-25} kg	20 mm

Users can observe that the radius increases as mass increases, showing a directly proportional relationship: $r \propto m$. Thus, heavier particles follow larger circular paths in a magnetic field.

Now vary the velocity by keeping other variables a constant. Users can now observe that the radius increases as velocity increases, confirming the proportionality: $r \propto v$.

Thus, faster-moving particles have wider circular trajectories in a uniform magnetic field.

Now vary the charge by keeping other variables constant. Users can now observe that the radius decreases as charge increases, confirming the inverse relationship:

$$r \propto \frac{1}{B}$$

Thus, a stronger magnetic field bends the particle's path more sharply, resulting in a smaller circular motion.

From this interactive user can infer that charged particles always move in circles in a uniform magnetic field if the velocity is perpendicular to the field. Increasing the mass or velocity results in a larger radius of motion. Increasing the charge or magnetic field strength results in a smaller radius of motion. This behavior follows directly from the Lorentz force equation, confirming fundamental principles of electromagnetism.

This simulation provides an interactive, visual approach to understanding how charged particles behave in magnetic fields, reinforcing both theoretical knowledge and mathematical relationships in physics.

1. Set the values for velocity, charge and magnetic field strength as follows:

   velocity: 5×10^6 m s^{-1}
   charge: 1×10^{-16} C
   magnetic field strength: 1 T
2. Check the 'Show Radius' box and take note of its value.
3. Change the mass to each value shown in **Table 2** (without changing the other values). Write down the radius for each mass.

Table 2. Mass and radius.

Mass	Radius
1×10^{-25} kg	
2×10^{-25} kg	

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Mass	Radius
3×10^{-25} kg	
4×10^{-25} kg	

1. Describe the pattern observed, and state one possible conclusion that could be drawn from the data.
2. Repeat Steps 3 and 4, creating tables for:
   (a) velocity and radius
   (b) charge and radius
   (c) magnetic field strength and radius.

We will now derive a mathematical expression for the radius. A particle with charge q is moving perpendicular to a magnetic field with strength B at a speed v. The force acting on the particle is given by:

$$F = qvB$$

This magnetic force is the centripetal force that causes the circular motion. Centripetal force is given by:

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

and so:

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

Rearranging this equation to make r the subject gives:

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

Study skills

The equation for the radius of the path of a charged particle in a magnetic field is not given in the DP physics data booklet. However, you should be able to derive this equation.

Student view

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Worked example 1

An electron is accelerated from rest by a potential difference of 250 V. It enters a magnetic field that is into the screen and has a strength of 0.250 T. The electron's path is one quarter of a circle.

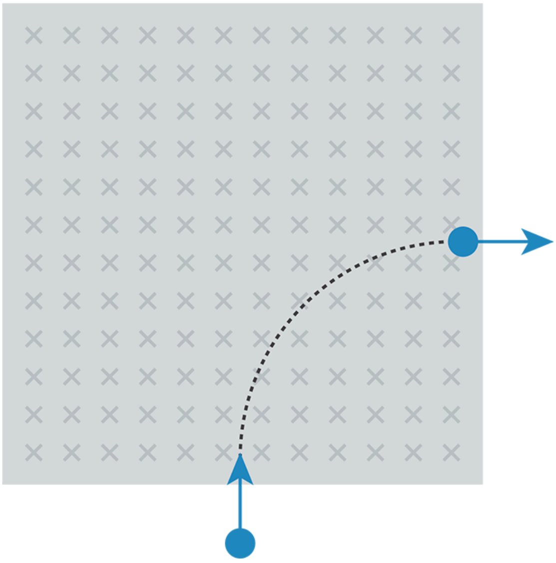

Figure 3. An electron's path in a magnetic field.

More information for figure 3

The diagram illustrates the path of an electron as it moves through a magnetic field. The background contains a grid of "X" marks representing the magnetic field, oriented into the page. A solid line starts from the bottom left corner of the image, curving upwards and to the right, indicating the electron's trajectory. The path resembles a quarter circle, consistent with the influence of a magnetic field on a charged particle. The arrow at the bottom left marks the starting point of the electron within the field.

[Generated by AI]

1. Determine the speed of the electron when entering the magnetic field.
2. Calculate the radius of the path followed by the electron.
3. Determine the time it takes the electron to exit the magnetic field.

(Elementary charge, $e = 1.60 \times 10^{-19}$ C; electron rest mass, $m_e = 9.110 \times 10^{-31}$ kg)

$$V = 250 \text{ V}$$

Student
view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

$B = 0.250\text{ T}$

$m = 9.110\times10^{-31}\text{ kg}$

$q = 1.60\times10^{-19}\text{ C}$

1. When an electron is accelerated from rest through a potential difference of 250 V, its kinetic energy is 250 eV:

$$250\times1.60\times10^{-19} = 4.00\times10^{-17}\text{ J}$$

$$E_\text{k} = \frac{1}{2}mv^2$$

$$4.00\times10^{-17} = \frac{1}{2}\times9.110\times10^{-31}\times v^2$$

$$v = 9.37\times10^{6}\text{ m s}^{-1}\text{ (3 s.f.)}$$

2. $r = \dfrac{mv}{qB}$

$$r = \frac{9.110\times10^{-31}\times9.37\times10^{6}}{1.60\times10^{-19}\times0.250}$$

$$r = 2.13\times10^{-4}\text{ m (3 s.f.)}$$

3. To find the time taken, find the period of rotation:

$$T = \frac{2\pi r}{v}$$

$$T = \frac{2\times\pi\times2.13\times10^{-4}}{9.37\times10^{6}}$$

$$T = 1.43\times10^{-10}\text{ s (3 s.f.)}$$

Since the electron stays in the magnetic field region for a quarter of a circle, divide the period by 4:

$$\text{time} = \frac{T}{4} = 3.58\times10^{-11}\text{ s (3 s.f.)}$$

Student view

Even on the tiny scales of subatomic particles, Newton's laws still hold.

Worked example 2

Using Newton's second law, derive an expression for the period of rotation for a charged particle inside a magnetic field moving at speed *v* perpendicular to the field and show that it is independent from the particle's speed.

The centripetal force is the magnetic force acting on the particle, so:

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

The centripetal acceleration, $\frac{v^2}{r}$, can be written in terms of the period T as $\frac{4\pi^2 r}{T^2}$ (as shown in section 1.3.A (/study/app/math-aa-hl/sid-423-cid-762593/book/space-time-and-motion-id-45160/) of the DP physics data booklet):

$$\frac{m4\pi^2 r}{T^2} = qvB$$

Rearranging to make T the subject:

$$T = \sqrt{\frac{4\pi^2 mr}{qvB}}$$

We have previously seen that the radius of the motion is given by $r = \frac{mv}{qB}$. Substituting this into the equation above gives:

$$T = \sqrt{\frac{4\pi^2 m}{qvB} \times \frac{mv}{qB}}$$

$$= \sqrt{\frac{4\pi^2 m^2}{q^2 B^2}}$$

$$= \frac{2\pi m}{qB}$$

This result shows that the period is independent of the particle's speed v. The period depends only on the particle's mass and charge, and the strength of the magnetic field.

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By adjusting the field strengths of magnetic and electric fields, a charged particle travelling at a particular speed can pass through undeflected.

Worked example 3

A charged particle enters a uniform magnetic field. The particle is moving perpendicular to the magnetic field, which has a strength of 0.150 T. The particle is moving at 2.30×10^4 m s^{-1}. An electric field is also present, so that the particle passes undeflected through both fields. Determine the magnitude of the electric field.

$$v = 2.30\times10^4 \text{ m s}^{-1}$$

$$B = 0.150 \text{ T}$$

The electric force and magnetic force are equal in magnitude:

$$F_{\text{electric}} = F_{\text{magnetic}}$$

$$qE = qvB$$

$$\begin{aligned} E &= vB \\ &= 2.30\times10^4\times0.150 \\ &= 3450 \text{ N C}^{-1} \text{ (3 s.f.)} \end{aligned}$$

Charge to mass ratio for a charged particle in magnetic field

The radius of the path of a charged particle in a uniform magnetic field, in the absence of other forces, is given by:

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

The equation can be rearranged to find an expression in terms of the particle's charge and mass:

$$\frac{q}{m} = \frac{v}{rB}$$

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This equation can be used to determine the charge to mass ratio for a charged particle in a uniform magnetic field:

$$\text{charge to mass ratio} = \frac{v}{rB}$$

Worked example 4

Figure 4 shows the paths of subatomic particles as seen in a bubble chamber.

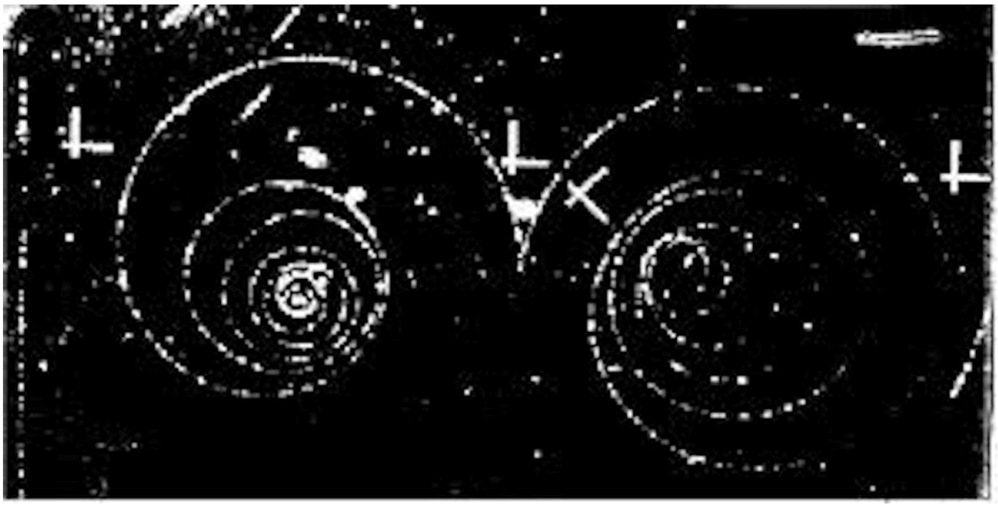

Figure 4. Bubble chamber photograph showing the paths of particles.

More information for figure 4

The image is a photograph from a bubble chamber showing the paths of subatomic particles. The chamber reveals several spiraling paths, some turning clockwise and others counterclockwise, indicating particles with opposite charges moving under the influence of a magnetic field. The paths are highlighted by white lines on a dark background, with two prominent spiral paths evident. Near the center, the image shows a point where an uncharged particle, previously invisible, seems to have split into two charged particles, each following its respective path in the opposite spiral directions. This image effectively visualizes the collision and transformation of particles in a bubble chamber.

[Generated by AI]

The bubble chamber has a 4.75×10^{-3} T magnetic field directed out of the screen (or page). Assume that the particles have a path in the plane of the screen (or page). In this photograph an uncharged particle (which leaves no track) travels upwards from the bottom and, near the middle of the photograph, it turns into a pair of new particles which have equal and opposite charges.

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Each of these particles moves with initial radius 8.55 mm and initial speed 0.0240c, where c is the speed of light. (The radius of each path decreases over time as the particles lose energy.) The effects of gravity can be ignored.

1. Deduce the type of charge on each of the two new particles.
2. Determine the charge to mass ratio of each of the two new particles.
3. Compare your answer to question 2 with the charge to mass ratio of an electron.

Solution steps	Calculations
Step 1: Use a suitable rule to find the types of charge on the particles.	The particle that follows the left-hand spiral has an initial velocity that is up the page, and experiences a force that is initially to the left. This is opposite to the direction predicted by the right-hand slap rule (since if you point your fingers out of the page and your thumb upwards, your palm, showing the force direction, faces towards the right). Therefore the left-hand particle must be negatively charged. The particle that follows the right-hand spiral obeys the right-hand slap rule (since the rule predicts a force to the right and that is what the photograph shows), so it must be positively charged.
Step 2: Write out the values given in the question and convert the values to units that can be used in equations.	$B = 4.75 \times 10^{-3}\ \mathrm{T}$ $r = 8.55\ \mathrm{mm}$ $= 8.55 \times 10^{-3}$ $v = 0.0240c$ $= 0.0240 \times 3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}$ $= 7.20 \times 10^{6}\ \mathrm{m\ s^{-1}}$
Step 3: Equate the centripetal force to the magnetic force and use this to determine $\frac{q}{m}$.	$\text{Centripetal force} = \text{magnetic force}$ $\frac{mv^2}{r} = qvB$ Divide both sides by v and then rearrange to make the charge to mass ratio, $\frac{q}{m}$, the subject: $\frac{q}{m} = \frac{v}{Br}$ $= \frac{7.20 \times 10^{6}}{4.75 \times 10^{-3} \times 8.55 \times 10^{-3}}$ $= 1.77 \times 10^{11}\ \mathrm{C\ kg^{-1}}$

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Solution steps	Calculations
Step 4: Compare with the charge to mass ratio of an electron.	For an electron: $q = 1.60 \times 10^{-19}\ \text{C}$ $m = 9.11 \times 10^{-31}\ \text{kg}$ $\frac{q}{m} = \frac{1.60 \times 10^{-19}}{9.11 \times 10^{-31}} = 1.76 \times 10^{11}\ \text{C kg}^{-1}$ This is very close to the value for the two particles in the photograph, so it is likely that one of them is an electron and the other is a particle with the same mass as an electron but opposite charge.

Use the activity to check your understanding of how to predict the direction in which a charged particle will move in a uniform magnetic field, and how to calculate the radius of its path.

Activity

- **IB learner profile attribute:**
  - Knowledgeable
  - Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Pair activity

Look at the simulation of a charged particle in a magnetic field in **Interactive 2.**

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Interactive 2. Motion of a charged particle in a magnetic field.

More information for interactive 2

This interactive simulation titled “Motion of a Charged Particle in a Magnetic Field” visually represents the motion of a charged particle in a uniform magnetic field, allowing users to explore how various physical parameters mass, velocity, charge, and magnetic field strength affect the radius of the particle's circular path. The simulation is based on the Lorentz force, which governs the motion of charged particles in electromagnetic fields.

When a charged particle moves perpendicularly to a uniform magnetic field, it experiences a force that acts perpendicular to its velocity, causing it to move in a circular trajectory. The radius of this circular motion, r, is given by the equation.

The radius of the particle’s circular path is determined by the equation:

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

Here r is the radius of the circular motion, m is the mass of the particle, m is the velocity of the particle, q is the charge of the particle, and B is the magnetic field strength.

Set the initial values of velocity as 5×10^{6} m/s, charge as 1×10^{-16} C and the magnetic field strength as 1 T as per the requirement of the surrounding data. Set the mass of the particle as 1×10^{-25} kg. Enable the "Show Radius" feature to display the radius of the circular path. The radius of the circular path followed by the positive charge is now displayed as 5 mm.

Vary different parameters one at a time while keeping the others constant to observe patterns in the relationship between the radius and each variable. Now, vary the mass while keeping the other variables unchanged. The data is shown in the table below:

Mass	Radius
1×10^{-25} kg	5 mm
2×10^{-25} kg	10 mm

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view

Mass	Radius
3×10^{-25} kg	15 mm
4×10^{-25} kg	20 mm

Users can observe that the radius increases as mass increases, showing a directly proportional relationship: $r \propto m$. Thus, heavier particles follow larger circular paths in a magnetic field.

Now vary the velocity by keeping other variables a constant. Users can now observe that the radius increases as velocity increases, confirming the proportionality: $r \propto v$.

Thus, faster-moving particles have wider circular trajectories in a uniform magnetic field.

Now vary the charge by keeping other variables constant. Users can now observe that the radius decreases as charge increases, confirming the inverse relationship:

$$r \propto \frac{1}{B}$$

Thus, a stronger magnetic field bends the particle's path more sharply, resulting in a smaller circular motion.
From this interactive user can infer that charged particles always move in circles in a uniform magnetic field if the velocity is perpendicular to the field. Increasing the mass or velocity results in a larger radius of motion. Increasing the charge or magnetic field strength results in a smaller radius of motion. This behavior follows directly from the Lorentz force equation, confirming fundamental principles of electromagnetism.
This simulation provides an interactive, visual approach to understanding how charged particles behave in magnetic fields, reinforcing both theoretical knowledge and mathematical relationships in physics.

1. Choose values for mass, velocity, charge and magnetic field strength. Enter these values into the simulation and show them to your partner.
2. Your partner decides whether the particle will rotate clockwise or anticlockwise, and calculates the radius of its path in the shortest possible time.
3. Switch roles.
4. After predicting successfully how the particle will rotate and calculating the radius of its path, record the time it takes each of you to do so. The quickest time wins.

5 section questions

Student view

Question 1

SL HL Difficulty:

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When a charged particle moves perpendicular to a magnetic field, it follows a circular path. The radius of this path is proportional to the 1 mass ✓ of the particle and the speed at which it is travelling. The radius is inversely proportional to the 2 charge ✓ of the particle and the 3 magnetic ✓ field strength.

Accepted answers and explanation

#1 mass

#2 charge

#3 magnetic

General explanation

For a particle with charge q is moving perpendicular to a magnetic field with strength B at a speed v, the radius is determined by:

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

Therefore, the radius of this path is proportional to the mass of the particle and the speed at which it is travelling, and it is inversely proportional to the charge of the particle and the magnetic field strength.

Question 2

SL HL Difficulty:

An electron experiences a zero resultant force when passing perpendicularly between two parallel plates, 5.0 cm apart, with a potential difference of 120 V. What is the magnitude of the magnetic field if the electron is moving at 2×10^5 m s^{-1}?

1 12 mT ✓

2 0.12 mT

3 6.0 mT

4 0.60 mT

Explanation

$$d = 5.0 \text{ cm}$$
$$= 0.05 \text{ m}$$

$$V = 120 \text{ V}$$

$$v = 2\times10^5 \text{ m s}^{-1}$$

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

$$E = \frac{120}{0.05}$$
$$= 2400 \text{ V m}^{-1}$$

$$F = e \times 2400 \text{ V m}^{-1}$$

As there is no resultant force,

$$evB = e \times 2400 \text{ V m}^{-1}$$

$$2 \times 10^5 \times B = 2400 \text{ V m}^{-1}$$

$$B = 0.012$$
$$= 12 \text{ mT}$$

Question 3

SL HL Difficulty:

Two identical charged particles move in circular paths at right angles to a uniform magnetic field. The radius of particle 2 is twice that of particle 1. Determine the ratio:

$$\frac{\text{kinetic energy of particle 1}}{\text{kinetic energy of particle 2}}$$

1 $\frac{1}{4}$ ✓

2 $\frac{1}{2}$

3 4

4 2

Explanation

The particles are identical and the radius of the path is proportional to the velocity, so:

$$E_{\mathrm{k}} \propto v^2$$
$$v_2 = 2v_1$$
$$E_{\mathrm{k}2} = 4E_{\mathrm{k}1}$$

$$\frac{\text{kinetic energy of particle 1}}{\text{kinetic energy of particle 2}} == \frac{1}{4}$$

Student view

Alternative method:

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$$\frac{\text{kinetic energy of particle 1}}{\text{kinetic energy of particle 2}} == \frac{\frac{1}{2}\times m_1\times v_1^2}{\frac{1}{2}\times m_2\times v_2^2}$$

Simplify their masses since they are identical:

$$\begin{aligned}
&= \frac{v_1^2}{v_2^2} \\
&= \left(\frac{v_1}{v_2}\right)^2 \\
&= \left(\frac{\frac{r_1\times q_1\times B}{m_1}}{\frac{r_2\times q_2\times B}{m_2}}\right)^2 \\
&= \left(\frac{r_1}{r_2}\right)^2 \\
&= \left(\frac{1}{2}\right)^2 \\
&= \frac{1}{4}
\end{aligned}$$

Question 4

SL HL Difficulty:

An electron is moving at a speed of 2.5×10^5 m s^{-1} through a uniform magnetic field with a strength of 28.0 mT. The velocity of the electron is at 30° to the magnetic field. What is the magnitude of the acceleration experienced by the electron?

1 6.15×10^{14} m s^{-2} ✓

2 6.15×10^{17} m s^{-2}

3 1.21×10^{15} m s^{-2}

4 1.21×10^{18} m s^{-2}

Explanation

$m = 9.110\times10^{-31}$ kg

$q = 1.60\times10^{-19}$ C

$v = 2.5\times10^5$ m s^{-1}

$$\begin{aligned}
B &= 28.0 \text{ mT} \\
&= 0.028 \text{ T}
\end{aligned}$$

$\theta = 30^\circ$

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$$F = ma$$

$$qvB \times \sin 30^\circ = m \times a$$

$$a = \frac{qvB \times \sin 30^\circ}{m}$$
$$= \frac{1.60 \times 10^{-19} \times 2.5 \times 10^5 \times 0.028 \times \sin 30^\circ}{9.110 \times 10^{-31}}$$
$$= 6.15 \times 10^{14} \text{ m s}^{-2} \text{ (3 s.f.)}$$

Question 5

SL HL Difficulty:

A particle with mass *m* and charge *q* follows a circular path with radius *r* while moving through a uniform magnetic field with strength *B*. What is the magnitude of the change in momentum of the particle during half a period?

1 $2rqB$ ✓

2 $\frac{2r}{qB}$

3 $\frac{r}{2qB}$

4 $\frac{2qB}{r}$

Explanation

In half a period, the particle's velocity is reversed:

$$\text{magnitude of change of momentum} = 2mv$$

The particle's speed can be expressed as:

$$v = \frac{rqB}{m}$$

$$\text{magnitude of change of momentum} = 2m\left(\frac{rqB}{m}\right)$$
$$= 2rqB$$

Student view

D. Fields / D.3 Motion in electromagnetic fields

Current and magnetic fields

D.3.5: Magnitude and direction of the force on a current-carrying conductor in a magnetic field

D.3.6: Force per unit length between parallel wires

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Learning outcomes

By the end of this section you should be able to:

- Describe that a current-carrying conductor in a magnetic field experiences a resultant magnetic force equal to the sum of the forces experienced by all the charged particles moving through it.
- Predict the direction of the force on a current-carrying conduction in a magnetic field, and use the equation:

$$F = BIL\sin\theta$$

- Explain that two parallel current-carrying conductors will exert a force on one another.
- Predict the directions of the forces on two parallel current-carrying conductors, and use the equation:

$$\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$$

How are electric currents affected by the magnetic fields around them?

When electrons flow through a conductor, a magnetic field is produced around the conductor (see subtopic D.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/)). A charged particle moving in such a way that its velocity has a non-zero component perpendicular to a magnetic field will experience a force (later in this section).

By connecting these ideas, we can predict that a current-carrying conductor in an external magnetic field will experience a force that is the resultant of all the forces experienced by the electrons that are moving inside (**Video 1**).

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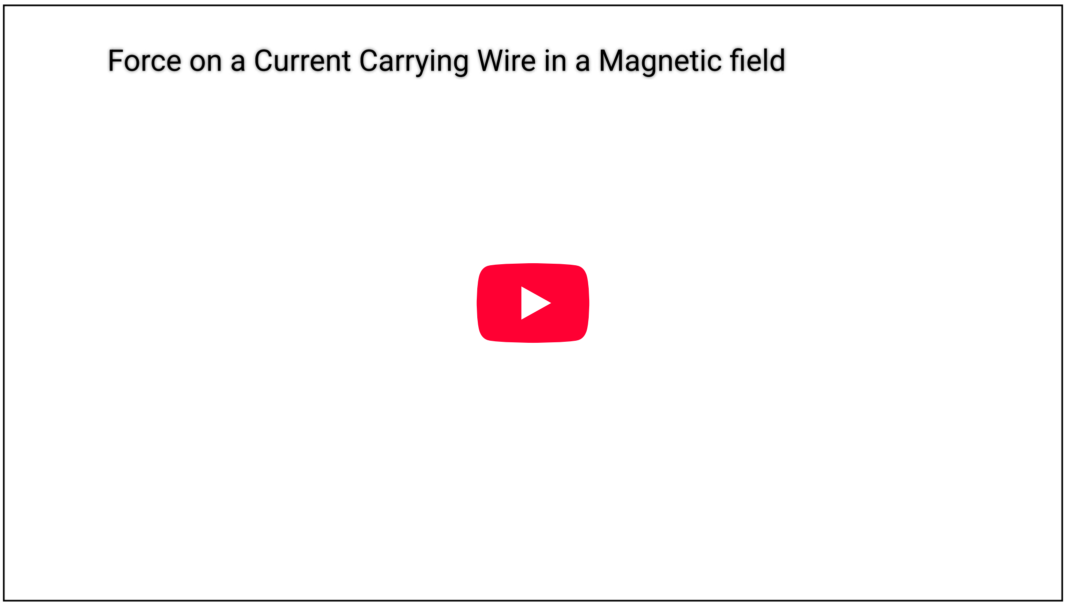

Video 1. Force on a current carrying conductor in a magnetic field.

Force on a current-carrying conductor in a magnetic field

If a current-carrying conductor is placed in a magnetic field, each of the moving electrons experiences a magnetic force that is perpendicular to its velocity and proportional to its speed. Every moving electron experiences this force, and so the conductor will experience a total force in a direction that is perpendicular to the flow of the current.

The magnitude of the force on a current-carrying conductor is proportional to the length of the conductor, since this length is proportional to the number of electrons that are contributing to the total force.

Concept

The force on a straight current-carrying conductor in a magnetic field has:

- a **direction** that is perpendicular to the direction of current flow and the external magnetic field
- a **magnitude** that is proportional to the strength of the magnetic field, the magnitude of the current, and the length of the conductor.

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Direction of force on a current-carrying conductor

You can predict the direction of the force by using the left-hand rule (see section D.3.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/motion-of-a-charged-particle-in-a-uniform-2-id-45418/)).

It is important to remember that conventional current is defined as having positive charge carriers for the electric current. The real flow of the (negative) electrons is opposite to conventional current.

Exercise 1

Click a question to answer

It may be useful to consider the direction of the force on a conductor in multiple different orientations.

Exercise 2

Click a question to answer

Practical uses of forces on wires

One of the uses of a wire being pushed in a particular direction when placed in a magnetic field is the DC motor.

DC motors power a wide variety of modern devices such as battery-powered toy cars, electric toothbrushes, drones, and the fans inside some computers. These all work by the same physical principle – a current-carrying conductor experiences a force inside a magnetic field.

Video 2 shows how a DC motor works.

Student view

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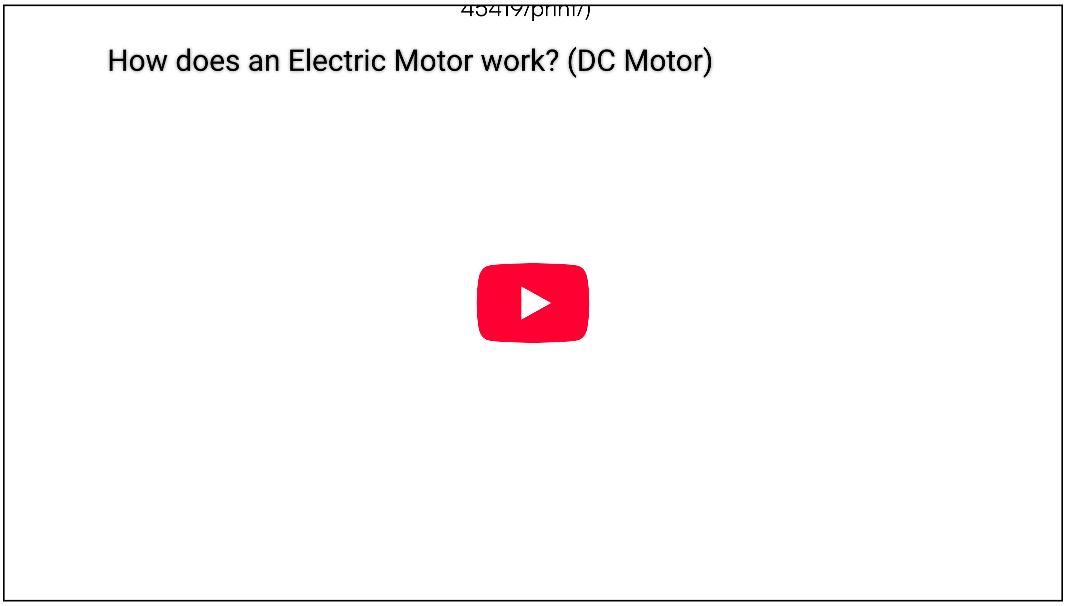

Video 2. How a DC motor works.

Magnitude of the force on a current-carrying conductor

When a current flows through a conductor in a uniform magnetic field, a force is experienced by the conductor. **Figure 1** shows the magnetic fields around two current-carrying wires and the directions of the forces acting on the wires.

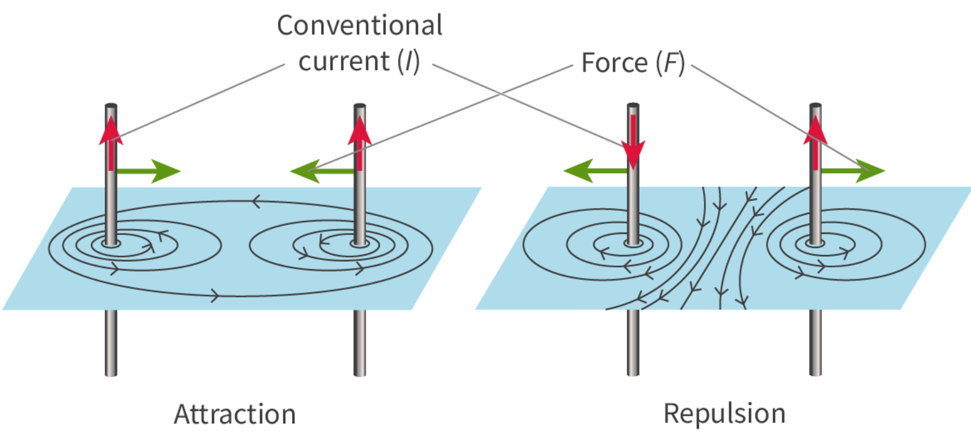

Figure 1. The magnetic fields around parallel current-carrying wires, and the directions of the forces acting.

More information for figure 1

The diagram illustrates the magnetic fields and forces around two wires with parallel current flows. It is divided into two parts: the left section demonstrates the attraction between two wires carrying currents in the same direction. In this part, the wires are vertical with concentric circular magnetic field lines around them, moving counterclockwise. Arrows indicate the conventional currents (I) going upwards and the resultant forces (F) are shown pushing towards each other, indicating attraction.

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The right section showcases repulsion between wires with opposite current directions. The setup is similar, but the current in one wire moves in the opposite direction, leading to opposing forces. The magnetic field lines are drawn similarly, but the forces (F) in this section push the wires apart, demonstrating repulsion. Labels include 'Conventional current (I)' and 'Force (F)', with arrows indicating directions of force and current.

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What factors will affect the magnitude of this force? See if you can predict them.

Just as for moving charges, the angle between the current and the magnetic field plays an important role when calculating the magnitude of the force experienced by a conductor. The other factors are: magnetic field strength, current, length of conductor.

The equation for the magnitude of the force is shown in **Table 1**.

Table 1. Equation for the magnitude of the force experienced by a conductor.

Equation	Symbols	Units
$F = BIL \sin \theta$	F = force	newtons (N)
	B = magnetic field strength	teslas (T)
	I = current	amperes (A)
	L = length of conductor	metres (m)
	θ = angle between current and field	degrees (°)

Study skills

The **force per unit length** acting on a conductor does not have a symbol; it is just the ratio of the force experienced by a conductor to its length:

$$\begin{aligned}\text{force per unit length} &= \frac{F}{L} \\ &= BI \sin \theta\end{aligned}$$

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In any problems, if you are asked to find the magnitude of any value (x) per unit (y), you should try to find the value of the ratio $x : y$ even if it is not given a name:

$$x \text{ per unit } y = \frac{\text{magnitude of value } x}{\text{magnitude of value } y}$$

Worked example 1

A wire placed along a north–south line carries a current of 4000 A. The Earth's magnetic field at the position of the wire has a magnitude of 4.8×10^{-5} T and runs from south to north. If the wire is placed 10° above the horizontal, what is the force per unit length experienced by the wire in mN m^{-1} (millinewtons per metre)? Give the answer to 2 s.f. without a unit.

$$I = 4000 \text{ A}$$

$$B = 4.8 \times 10^{-5} \text{ T}$$

$$\theta = 10^{\circ}$$

$$\frac{F}{L} = BI \sin\theta$$

$$\begin{aligned}\frac{F}{L} &= 4.8 \times 10^{-5} \times 4000 \sin 10^{\circ} \\ &= 0.03334 \text{ N m}^{-1} \\ &= 33.34 \text{ mN m}^{-1} \\ &= 33 \text{ mN m}^{-1} \text{ (to 2 s.f.)}\end{aligned}$$

Force per unit length between parallel wires

What happens when a current flows along two parallel wires? Why? Use the simulation in **Interactive 1** to explore what happens.

Student view

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Interactive 1. Forces between two current-carrying wires.

More information for interactive 1

This interactive demonstrates the force between two parallel current-carrying wires due to their induced magnetic fields. It allows users to explore how the interaction between the magnetic fields generated by each wire results in either an attractive or repulsive force. By adjusting the current in each wire and modifying the distance between them, users can observe the changes in both the magnitude and direction of the force, reinforcing key principles of electromagnetism.

The two wires, labeled as wire A and wire B, are positioned vertically in the visualization. Wire A is marked in orange, and wire B is marked in green. The background displays the induced magnetic field around the wires, helping users visualize how the fields interact. Users can control the current in each wire using sliders, with values shown in amperes. Another slider allows adjustments to the distance between the two wires. The force between the wires is represented by arrows, indicating whether the interaction is attractive or repulsive depending on the direction of the currents.

By enabling the option to display the induced magnetic fields from each wire, users can observe how the fields interact. When the currents in both wires flow in the same direction, the wires attract each other, as their magnetic fields combine in a way that pulls them together. Conversely, when the currents flow in opposite directions, the wires repel due to the opposing magnetic field interactions. This visualization directly demonstrates the fundamental principle that **parallel currents attract and anti-parallel currents repel.**

Users can also explore how the magnitude of the force changes based on the current and the separation distance between the wires. By increasing the current, the force becomes stronger, while increasing the distance between the wires weakens the force. This hands-on interaction helps users see how these variables influence the strength of the magnetic interaction.

Student view

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This interactive provides an intuitive and engaging way to explore the relationship between electric currents and magnetic forces. By experimenting with different values and visualizing the effects in real time, users can develop a deeper understanding of how moving charges generate magnetic fields and how these fields influence nearby conductors. It serves as a valuable tool for students and educators studying electromagnetism, offering a clear demonstration of the forces at play in current-carrying wires.

Select 'Show Forces' (bottom right). Adjust the current for each wire so the current is in the same direction. What direction are the forces in? What happens when the currents are in opposite directions? What happens when there is no current in one of the wires? What affects the size of the force between the wires? Select 'Show induced magnetic field from wire A' and 'Show induced magnetic field from wire B'. What do you notice about the field between the two wires when the currents are in the same direction? Opposite directions?

The two wires experience a force due to the interaction between the magnetic fields that are created around each wire. Each wire will simultaneously:

- produce a magnetic field around it
- interact with the magnetic field produced by the other wire, experiencing a force.

Worked example 2

Two parallel wires are carrying a current that is out of the screen.

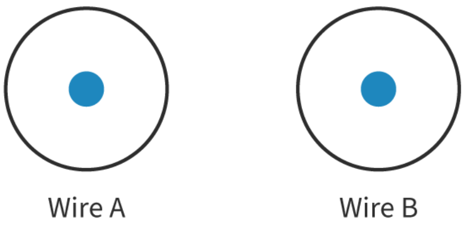

Figure 2. Wires carrying a current out of the screen.

More information for figure 2

The diagram illustrates two parallel wires carrying a current out of the screen. The image consists of two circles, each representing a wire. The circles are labeled 'Wire A' and 'Wire B', and each circle contains a blue dot in the center. The circles symbolize the cross-sections of the wires, and the blue dots indicate the centers where the currents are flowing outwards from the screen. There are no additional symbols or notations on the diagram apart from the labels 'Wire A' and 'Wire B'.

Student view

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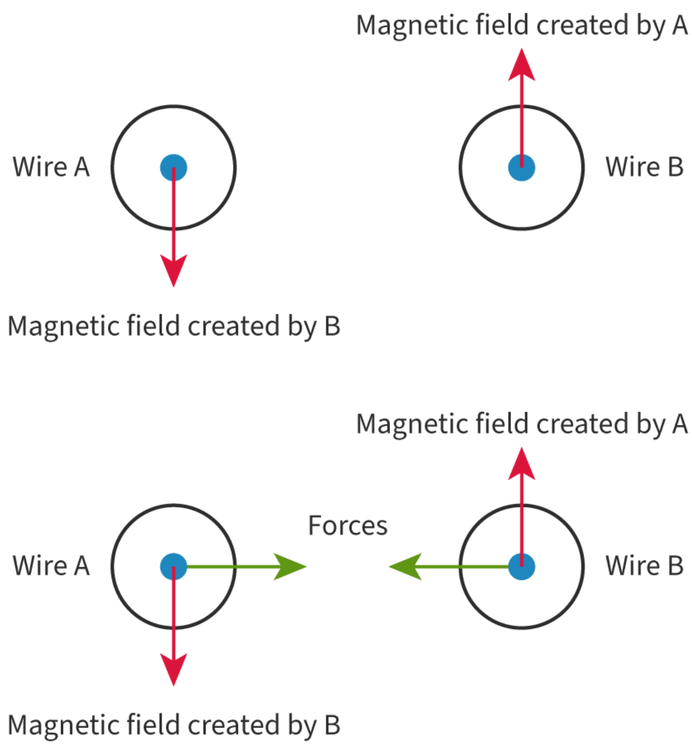
1. State the direction of the magnetic field created by A at the position of B, and created by B at the position of A.
2. Predict the direction of the force experienced by A due to the magnetic field created by B, and experienced by B due to the magnetic field created by A.



1. According to the right-hand rule for the magnetic field produced by a current-carrying wire, for both wires, the magnetic field lines can be represented as concentric circles running in an anticlockwise direction. The magnetic field created by A at the position of B is pointing upwards. The magnetic field created by B at the position of A is pointing downwards.

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2. According to the left-hand rule for a current in a magnetic field, the force experienced by A due to the magnetic field of B is acting to the right. The force experienced by B due to the magnetic field of A is acting to the left.

In **Worked example 1**, we discovered that the force of interaction is an attractive force. This is the case for any situation in which the currents flowing through two parallel wires are flowing in the same direction. For parallel wires, when the current flows in opposite directions, the force is a repulsive force. **Figure 3** shows the direction of current and force for two parallel wires.

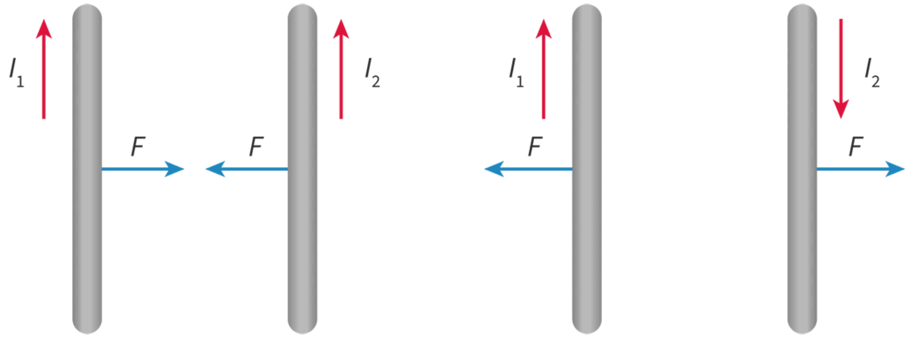

Figure 3. Forces and currents for two parallel wires.

More information for figure 3

The image is a diagram illustrating the forces and currents for two parallel wires. The wires are shown parallel to each other, with arrows indicating the direction of the electric current in each wire. One wire has its current flowing upwards, and the other downwards. The forces between the wires are also depicted with arrows, demonstrating an attractive force when the currents are in the same direction and a repulsive force when they are in opposite directions. Additionally, the diagram may include labels for current direction and force representation to clarify their interactions.

[Generated by AI]

The force between parallel current-carrying wires is:

- attractive if currents are flowing in the same direction
- repulsive if currents are flowing in opposite directions.

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The equation for the magnitude of the force between two parallel current-carrying wires is shown in **Table 2**.

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Table 2. Equation for the magnitude of the force between two parallel current-carrying wires.

Equation	Symbols	Units
$\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$	F = force	newtons (N)
	L = length of conductors	metres (m)
	μ_0 = permeability of free space	4π × 10^{-7} T mA^{-1} (section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) in the DP physics data booklet)
	I_1 = current in first wire	amperes (A)
	I_2 = current in second wire	amperes (A)
	r = distance between the wires	metres (m)

Theory of Knowledge

The permeability of free space, $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T\ m^{-1}}$, and the permittivity of free space, $\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{C^2\ N^{-1}\ m^{-2}}$, are two constants considered to be universal. They are related by:

$$\varepsilon_0 \times \mu_0 = \frac{1}{c^2}$$

where c is the speed of light.

This relationship led to the shift from explaining the Universe using Newton's laws of motion to explaining it using Einstein's laws of special relativity. This change in thinking about fundamental concepts is known as a **paradigm shift.**

What evidence is necessary for a paradigm shift to occur and be accepted in science? How is this different to a paradigm shift in the arts?

5 section questions

Student view

Question 1

SL HL Difficulty:

When a current-carrying conductor is 1 perpendicular ✓ to a magnetic field, it experiences a force per unit length that is proportional to the magnitude of the field and to the 2 current ✓ .

Accepted answers and explanation

#1 perpendicular
at right angles

#2 current
I

General explanation

When a current-carrying conductor is perpendicular to a magnetic field, it experiences a force per unit length that is proportional to the magnitude of the field and to the current. If an electric current flows through parallel wires in the same direction, the wires will experience an attractive force that is proportional to the currents running through the wires and inversely proportional to the separation between the wires.

Question 2

SL HL Difficulty:

Two parallel wires are separated by a distance of 0.500 cm. Both wires are carrying a current of 40.0 A, flowing in opposite directions. What is the magnitude of the force per unit length between the wires, and what is its nature?

	Magnitude	Nature
A	$0.0016\ \mathrm{N\ M^{-1}}$	Attractive
B	$6.4\ \mathrm{N\ M^{-1}}$	Attractive
C	$0.16\ \mathrm{N\ M^{-1}}$	Repulsive
D	$6.4 \times 10^{-2}\ \mathrm{N\ M^{-1}}$	Repulsive

1 D ✓

2 A

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3 C

4 B

Explanation

$$d = 0.500 \text{ cm}$$
$$= 0.005 \text{ m}$$

$$I = 40.0 \text{ A}$$

$$\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$$

$$\frac{F}{L} = 4\pi \times 10^{-7} \frac{40.0 \times 40.0}{2\pi \times 0.005}$$

$$\frac{F}{L} = 0.064$$
$$= 6.4 \times 10^{-2} \text{ N m}^{-1}$$

The force will be repulsive.

Question 3

SL HL Difficulty:

A wire is perpendicular to a magnetic field with a magnitude of 160 mT. What should the current through the wire be for it to experience a force per unit length of 0.1 N m^{-1}?

1 0.625 A ✓

2 16 mA

3 0.625 mA

4 16 A

Explanation

$$B = 160 \text{ mT}$$
$$= 0.160 \text{ T}$$

$$\frac{F}{l} = 0.1 \text{ N m}^{-1}$$

$$\frac{F}{l} = BI$$

$$0.1 = 0.160 \times I$$

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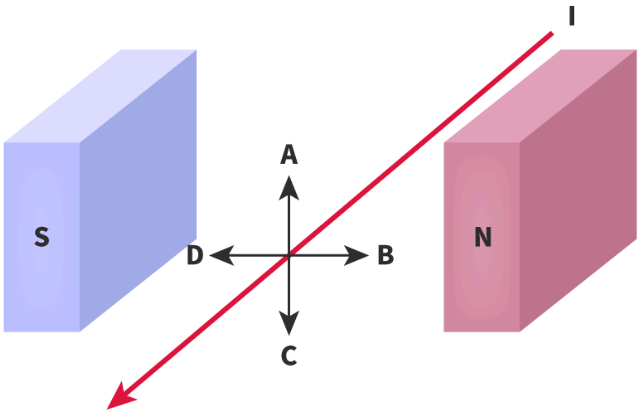
$I = 0.625 \text{ A}$

Question 4

SL HL Difficulty:

The diagram shows a current-carrying conductor in a magnetic field.



More information

Which arrow shows the direction of the force acting on the conductor?

1 C ✓

2 A

3 B

4 D

Explanation

The magnetic field of the magnet points from the north pole to towards the south pole. The left-hand rule for current in a magnetic field shows that the force will be downwards (C).

Question 5

SL HL Difficulty:

A solenoid consists of a wire coiled into a cylindrical shape. When an electrical current flows through the solenoid, there is a force of interaction between the different turns of the solenoid.

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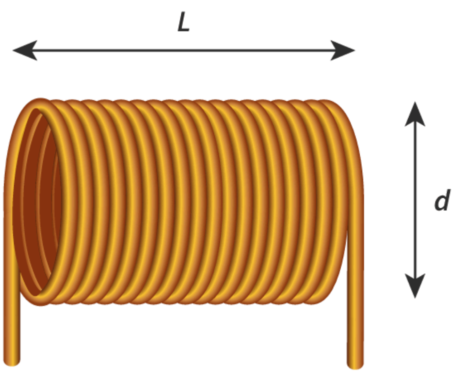

More information

Which of the following best describes the effect that increasing the current will produce in the solenoid?

1 There will be a decrease in the length *L* ✓

2 There will be a decrease in the diameter *d*

3 There will be an increase in the length *L*

4 There will be an increase in the diameter *d*

Explanation

Current will flow along consecutive turns of the solenoid in the same direction. This will produce an attractive force that will tend to compress the solenoid, decreasing its total length.

Summary and key terms

- When a particle with charge q is in an electric field with field strength E, the particle experiences a force of magnitude $F = qE$.
- In a uniform electric field, the force is constant. The charged particle has a linear path if the component of the velocity perpendicular to the field is zero, and a parabolic path if there is a non-zero component of the velocity perpendicular to the field.

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- When a particle with charge q is moving in a magnetic field of field strength B, it experiences a force if it has a non-zero component of its velocity perpendicular and to the field. The direction of the magnetic force is perpendicular to the velocity and to the magnetic field.
- The magnitude of the magnetic force is $F = qvB\sin\theta$ where θ is the angle between the velocity v and the magnetic field lines.
- The work done by the magnetic force on a charged particle is always zero, so the particle will move at a constant speed.
- The path followed by a charged particle moving inside a magnetic field is circular. It can be shown that the radius r of the path is given by $r = \frac{mv}{qB}$ where m, q and v are the mass, charge and speed of the particle respectively, and B is the magnetic field strength.
- When a conductor of length L carrying current I is in a magnetic field of field strength B, the conductor experiences a force that is perpendicular to the current and the field and has magnitude $F = BIL\sin\theta$ where θ is the angle between the current and the field lines.
- Two parallel wires carrying a current will experience a force of attraction if the currents are flowing in the same direction. If the currents are flowing in opposite directions, the force is repulsive. The magnitude of the force per unit length acting on each wire is $\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$ where r is the perpendicular distance between the wires.

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Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. When a charged particle moves in a magnetic field, it experiences a force that is to the magnetic field and to the particle's .
2. To determine the of the force acting on the particle, the is used.
3. The rule states that if the left first finger points in the direction of the and the second finger points in the direction of the , the thumb will point in the direction of the .

velocity | left-hand rule | perpendicular | current | direction | force | magnetic field

Check

Interactive 1. Understand the Direction and Nature of Magnetic Forces Using the Left-Hand Rule.

D. Fields / D.3 Motion in electromagnetic fields

Checklist

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/checklist-id-45422/print/) Assign

What you should know

After studying this subtopic, you should be able to:

- Predict the direction of the force on a charged particle in an electric field, and calculate its magnitude.
- Understand that the acceleration of a charged particle in an electric field is affected by the magnitude (and direction) of the field and the charge and mass

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of the particle.

- Predict and calculate changes in the kinetic energy and electric potential energy of a charged particle that moves through an electric field.
- Describe the motion of a charged particle moving through a uniform magnetic field.
- Describe and explain the motion of a charged particle in magnetic and electric fields at right angles to each other.
- Predict the direction of the force on a charged particle in a magnetic field, describe the path taken by the particle and use the equation:

$$F = qvB\sin\theta$$

- Predict the radius of the circular path followed by a charged particle moving in a uniform magnetic field.
- Describe how the path of a charged particle moving through a magnetic field can be used to determine properties of the particle.
- Describe that a current-carrying conductor in a magnetic field experiences a resultant magnetic force equal to the sum of the forces experienced by all the charged particles moving through it.
- Predict the direction of the force on a current-carrying conduction in a magnetic field, and use the equation:

$$F = BIL\sin\theta$$

- Explain that two parallel current-carrying conductors will exert a force on one another.
- Predict the directions of the forces on two parallel current-carrying conductors, and use the equation:

$$\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$$

D. Fields / D.3 Motion in electromagnetic fields

Investigation

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-id-45423/print/) Assign

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills – Asking questions and framing hypotheses based upon sensible scientific rationale

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Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/current-and-magnetic-fields-id- Assign

- **Time required to complete activity:** 40 minutes
- **Activity type:** Pair activity

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Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

The flow of electrons through a wire produces a magnetic field around the wire. When two current-carrying wires are placed parallel to each other, they experience a force of interaction. This force is attractive for currents flowing in the same direction and repulsive for currents flowing in opposite directions. The force is proportional to the currents running through each wire and inversely proportional to the distance between the wires. This can be expressed as:

$$F \propto \frac{I_1 I_2}{r}$$

When forces are expressed in newtons, currents in amperes, and distances in metres, a proportionality constant can be added to produce an equation. This is usually written as:

$$F = \mu_0 \frac{I_1 I_2}{2\pi r}$$

Your task

Design an experiment based on this equation to measure and verify the value of μ_0, the permeability of free space. Since you already know its value ($4\pi \times 10^{-7}$ T mA^{-1}), perform some calculations to gain understanding of the magnitudes that you would be designing an experiment for.

Defining variables

Define what your independent and dependent variables will be. These variables should allow you to determine the permeability of free space constant. For each of the variables, do some research on which instrument could be used to measure it. List all the variables that should be controlled during the experiment, given that a change in them might affect your measurements.

- Define the independent variable and describe how you will be measuring it.
- Define the dependent variable and describe how you will be measuring it.
- List the control variables and explain for each:
  - the reason it needs to be controlled
  - how it could be controlled.

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Experimental setup

Design apparatus that could be used to take the required measurements. Create labelled diagrams describing each piece of apparatus and provide instructions for its construction. The diagrams should contain enough information so that anyone can recreate the setup using your instructions only.

- Create labelled diagrams describing the experimental setup.
- Write instructions for setting up all the necessary equipment.

One way to measure a small force is to use an electronic balance. A mass reading on the balance can be converted into a force (since the balance shows 98.1 g when a force of 1.00 N acts downwards on it).

Estimating values

Perform the calculations to estimate the magnitudes the experiment may deal with. Do some research so that the range of values for the independent and dependent variables are realistic. This means that you keep each variable within certain limits and precisely define those limits.

You need to be aware that within an experiment, certain magnitudes are difficult to measure if they fall below certain values, and can be dangerous if they go beyond certain values.

Check that the apparatus used to take measurements can work within those boundaries. In order to calculate these values, use the given value for the permeability of free space constant.

- Define a lower and upper boundary for the independent and dependent variables.
- Describe why the defined boundaries for each variable are realistic in terms of what can be recreated in a laboratory without risking the safety of the experiment.

Procedure

Write a step-by-step procedure that could be followed in order to take enough measurements to allow the experimental determination of the permeability of free space constant. It should provide detailed instructions so that a reasonable amount of measurements are performed that would lead to an acceptable experimental uncertainty. Enough measurements should be taken so that the random errors are reduced to a reasonable value.

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Safety and environmental issues

List the safety precautions that should be considered when performing the experiment. You should also list all the things that should be considered so as to minimise the environmental impact of the experiment.

Processing

Describe how the raw data should be processed. The description should include how to create a graph on which a line of best fit could be drawn so that its equation could be used to determine the permeability of free space constant.

D. Fields / D.3 Motion in electromagnetic fields

Reflection

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47884/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-45416/).

- How do charged particles move in magnetic fields?
- What can be deduced about the nature of a charged particle from observations of it moving in electric and magnetic fields?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

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You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic D.3 Motion in electromagnetic fields

Help us improve the content and user experience.

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