



2021 Sec 4 Advanced Physics

Electromagnetism: Electric and Magnetic Fields

Name: _____ () Class: 4 / ____

Electric and Magnetic Fields

- Electric Fields
- Coulomb's Law
- Electric Fields from Point Charges
- Comparison between Electric Fields and Gravitation Fields
- Force on Current Carrying Conductors in Magnetic Fields
- Force on Moving Charges in Magnetic Fields
- Motion of Charged Particles in Uniform Electric Field and/or Magnetic Field

Learning Outcomes

- define electric field strength at a point as the electric force exerted per unit positive charge placed at that point
- recognise the analogy between certain qualitative and quantitative aspects of electric and gravitational fields
- recall and use Coulomb's law in the form $F = kq_1q_2 / r^2$ for the electric force between two point charges in free space or air
- recall and use $E = kQ / r^2$ for the electric field strength of a point charge in free space or air
- calculate the forces on charges in uniform electric fields
- describe the effect of a uniform electric field on the motion of charged particles
- recall and solve problems using the equation $F = BIL$, with directions as interpreted by Fleming's left-hand rule
- recall and solve problems using the equation $F = Bqv$
- describe and analyse deflections of beams of charged particles by uniform electric and uniform magnetic fields
- explain how electric and magnetic fields can be used in velocity selection for charged particles

1 Electric Fields

An electric field is the region in which an electric charge experiences an electric force.

The electric field strength, E , at a point in the field is the electric force F experienced per unit positive test charge placed at that point:

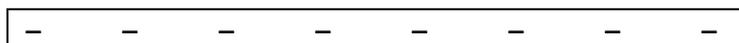
$$E = \frac{F}{q}$$

Example 1

A light charged particle of -1.0 mC is placed in a uniform electric field of 5.0 N C^{-1} .



○ ————— charged particle

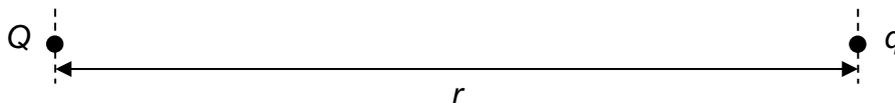


- Label the direction of the electric force on the particle.
- Determine the magnitude of the electric force experienced by the particle.

[upwards, $5.0 \times 10^{-3} \text{ N}$]

2 Coulomb's Law

When two point-charges are brought into proximity, they exert a force on each other.

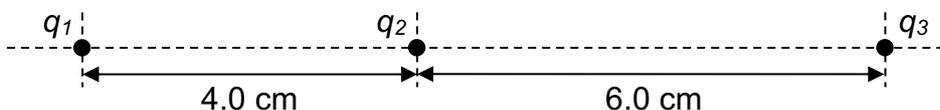


Coulomb's Law states that the **magnitude of the electric force** acting between two point-charges is **directly proportional to the product of the charges**, and **inversely proportional to the square of their distance apart**. The direction of the force is along the line joining the two charges.

$$F = \left| \frac{kQq}{r^2} \right|$$

where F : electric force
 Q and q : charge of the two point-charges
 r : distance between the point-charges
 k : Coulomb's constant = $8.99 \times 10^9 \text{ kg m}^3 \text{ s}^{-4} \text{ A}^{-2}$

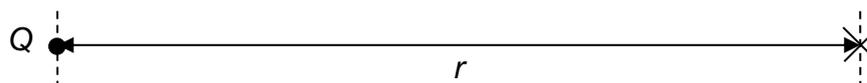
Example 2



The figure above shows three charges aligned along a straight line in vacuum. Calculate the resultant force experienced by q_2 given that $q_1 = +4.0 \mu\text{C}$, $q_2 = -2.0 \mu\text{C}$ and $q_3 = +3.0 \mu\text{C}$.

[30 N to the left]

3 Electric Fields from Point-Charges



By combining Coulomb's law with the definition of the electric field strength, it can be deduced that the electric field strength E exerted by a point charge Q at a distance r will be:

$$E = \left| \frac{kQ}{r^2} \right|$$

Example 3

A positively charged particle Q_1 has charge of 3.0×10^{-15} C. Another positively charged particle Q_2 has charge of 5.0×10^{-15} C. The two charged particles are placed 5.0 cm apart.

Determine the distance of a point N, measured from Q_1 , where the resultant electric field strength due to both charges is zero.

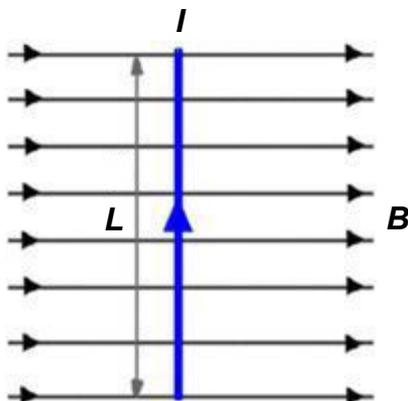
[0.022 m]

4 Comparison of Electric Fields with Gravitation Fields

	Gravitational Field	Electric Field
Origin of forces	Due to mass interaction	Due to charge interaction
Nature of force	Attractive	Attractive or repulsive
Quantitative Law	Newton's Law of Gravitation: $F_g = \frac{Gm_1m_2}{r^2}$	Coulomb's Law: $F_E = \left \frac{kQq}{r^2} \right $
Field Strength	Force per unit mass: $g = \frac{F_g}{m}$	Force per unit positive charge: $E = \frac{F_E}{q}$
Field set up by isolated mass/charge	$g = \frac{GM}{r^2}$	$E = \frac{kQ}{r^2}$

5 Force on Current Carrying Conductors in Magnetic Fields

When a current carrying conductor is placed in a magnetic field, it experiences a force. The direction of the force can be determined using Fleming's left hand rule if the directions of the current and magnetic field are known.



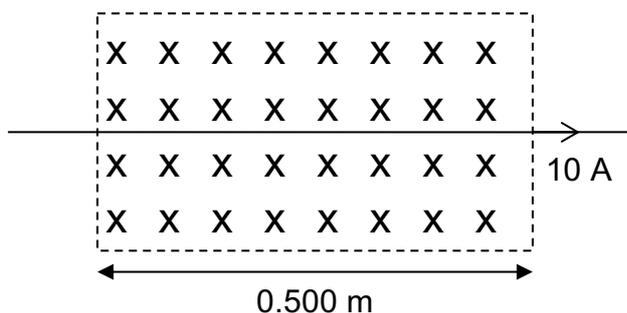
The magnitude of the force for a current carrying conductor that is *perpendicular* to the direction of the magnetic field can be calculated by:

$$F = BIL$$

where F : force acting on a conductor of length L
 B : magnetic flux density
 I : magnitude of current
 L : length of conductor

Example 4

A 0.500 m wire carrying a 10 A current is placed in a magnetic field of 2.0 T. State the direction of the force acting on the wire and determine its magnitude.

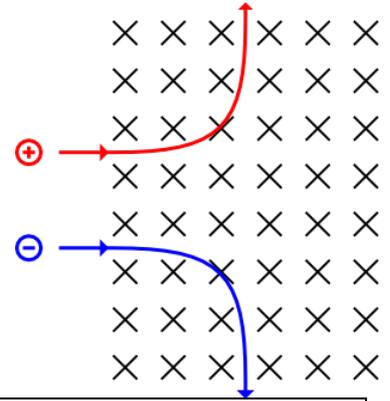


[upwards, 10 N]

6 Force on Moving Charges in Magnetic Fields

As current essentially consists of moving charges, it can be deduced that a moving charged particle must experience a magnetic force.

Consider a charged particle travelling at constant speed, *perpendicular* to the direction of a magnetic field. The magnetic force experienced by the charged particle is given by:



$$F = Bqv$$

where F : force acting on the charged particle
 B : magnetic flux density
 q : magnitude of charge
 v : velocity of the charged particle

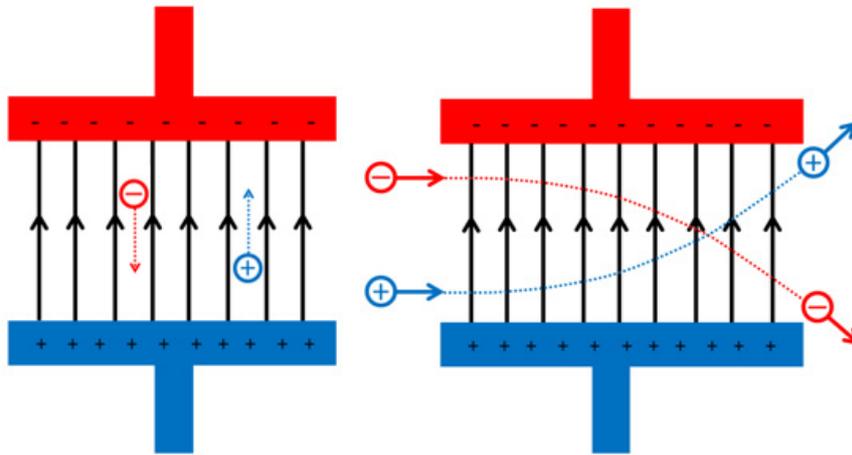
Example 5

Show that $F = Bqv$ can be derived from $F = BIL$.

7 Motion of Charged Particles in Uniform Electric Field and/or Magnetic Field

7.1 Motion of Charged Particles in Uniform Electric Field

When charged particles enter a uniform electric field, they experience an electric force that will be parallel to the direction of the electric field.



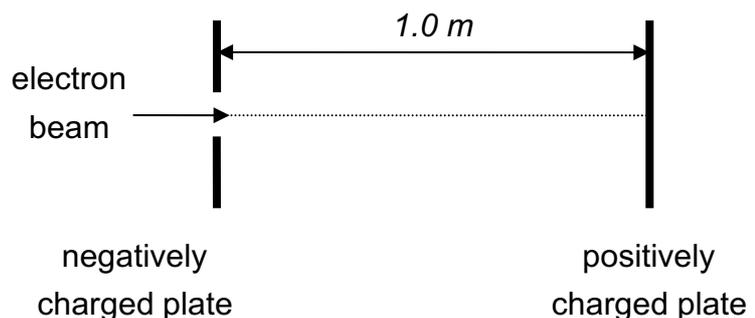
When the charged particles are initially stationary or moving parallel to the direction of the electric field, the motion will be linear and can be directly analysed using equations of motion.

Otherwise, the charged particles will move in a parabolic path and the trajectory can be analysed as projectile motion, which will require breaking down the motion into two dimensions.

Example 6

Consider a beam of electrons accelerated from rest through an electric field of 500 N C^{-1} in the region between two parallel charged plates 1.0 m apart.

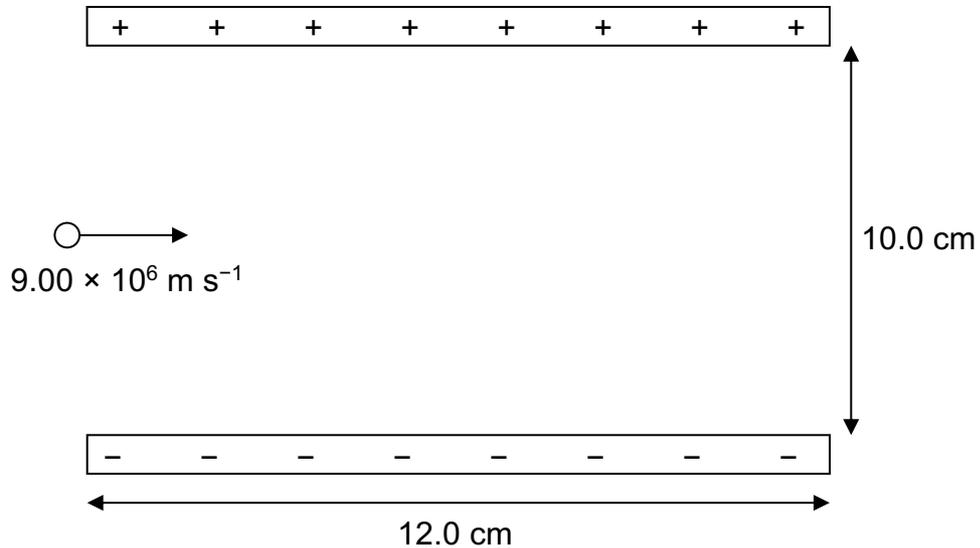
Given that the mass of an electron is $9.11 \times 10^{-31} \text{ kg}$ and its charge is $-1.60 \times 10^{-19} \text{ C}$, determine the time taken for the electrons to hit the far plate. Ignore the weight of the electron.



$[1.5 \times 10^{-7} \text{ s}]$

Example 7

An electron is projected with a speed of $9.00 \times 10^6 \text{ m s}^{-1}$ into the space between two 12.0 cm parallel conducting plates with electric field strength $1.60 \times 10^3 \text{ N C}^{-1}$. The plates are separated by 10.0 cm. The mass of an electron is $9.11 \times 10^{-31} \text{ kg}$ and its charge is $-1.60 \times 10^{-19} \text{ C}$.

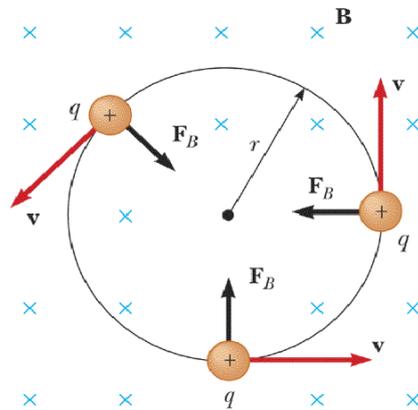


- (a) Determine the time taken for the electron to emerge from the field.
- (b) Calculate the acceleration of the electron when it is between the plates. You may ignore the weight of the electron.
- (c) Calculate the total vertical deflection of the electron due to the electric field.
- (d) Sketch the path taken by the electron to emerge from the electric field.

$[1.33 \times 10^{-8} \text{ s}, 2.81 \times 10^{14} \text{ m s}^{-2}, 0.0250 \text{ m}]$

7.2 Motion of Charged Particles in Uniform Magnetic Field

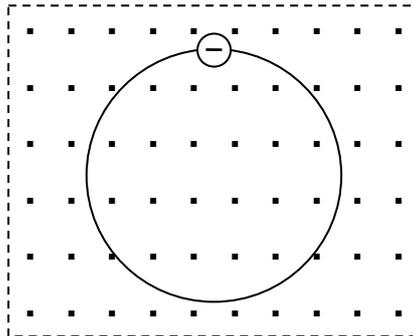
When charged particles enter a uniform magnetic field, they experience a magnetic force that will be perpendicular to the direction of the magnetic field and perpendicular to the direction of motion.



Therefore, the charged particles will move along the arc of a circle.

Example 8

An electron moves in a circular path in vacuum under the influence of a magnetic field.



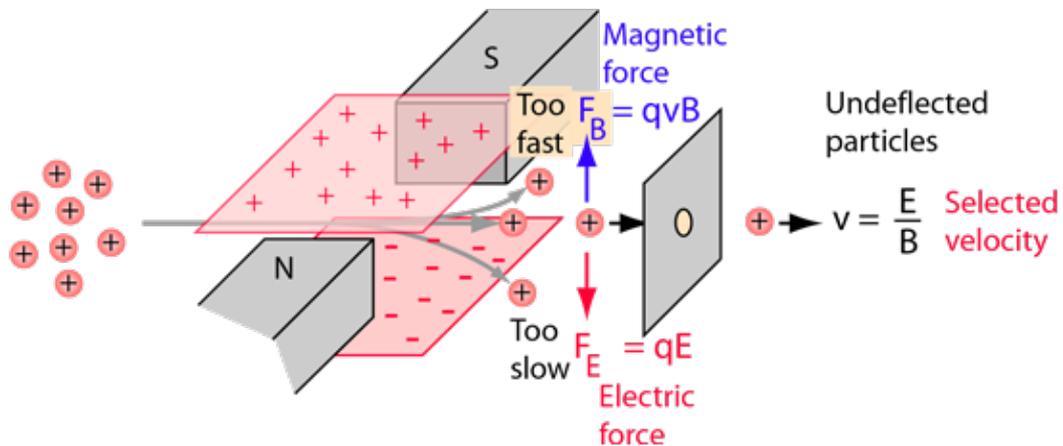
The radius of the path is 0.010 m and the magnetic flux density is 0.020 T. Given that the mass of the electron is 9.11×10^{-31} kg and the charge on the electron is -1.6×10^{-19} C.

- Determine if the motion of the electron is clockwise or anticlockwise.
- Determine the velocity of the electron.

[anticlockwise, 3.5×10^7 m s⁻¹]

7.3 Velocity Selectors

Uniform electric and magnetic fields could be set up perpendicular to each other such that they produce deflections in opposite directions. The idea is used in a velocity selector, which is an instrument that selects and emits a stream of charged particles of a specific velocity.



In the diagram above, a beam of positively charged particles with a range of velocities are made to pass through a region of electric field and magnetic field applied perpendicular to each other. In the region, the positively charged particles experience an upward magnetic force and a downward electric force.

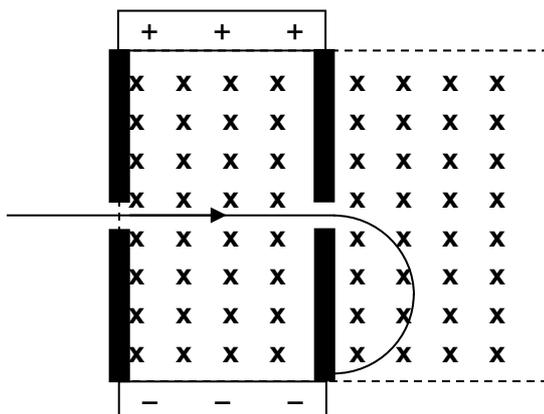
For the particles to pass through undeflected, the electric force and magnetic force must be equal in magnitude:

$$\begin{aligned}F_B &= F_E \\qvB &= qE \\v &= \frac{E}{B}\end{aligned}$$

Therefore, particles which emerge undeflected will have the same speed, determined by the ratio above. Charged particles of a particular desired speed can be "selected" and emitted by adjusting the ratio.

Example 9

After passing through a velocity selector as shown in the diagram below, a beam of electrons move in a circular path of radius 5.0 cm.



Given the electric field strength is 40 N C^{-1} , the mass of the electron is $9.11 \times 10^{-31} \text{ kg}$ and its charge is $-1.6 \times 10^{-19} \text{ C}$, determine the magnetic flux density that is applied.

$[6.7 \times 10^{-5} \text{ T}]$