A2 Level Physics

Chapter 12 – Magnetic Fields

12.2.1 Motion of Charged Particles

Notes

www.tutorpacks.co.uk

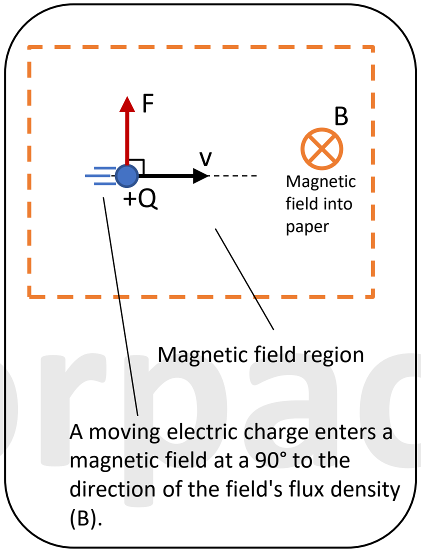
@tutorpacks

Force on moving charges in a magnetic field

A moving electric charge generates an electric current, which causes a magnetic field to form around it. As a result, when an electric charge moves through a magnetic field, the two fields interact, causing the charge to experience a force.

The size of the force (F) acting on a moving charge in a magnetic field is determined by the following factors:

- The size of the charge (Q).
- The moving charge's speed (v).
- The magnetic flux density (B) of the field.
- The angle (θ) formed between the direction of motion and the field.



Consider a charge, $+Q$, moving at right angles to a magnetic field of flux density, B, at a speed of v (shown opposite).

In time, t, the charge moves through distance, $L = vt$.

The current due to the moving charge, $I = \frac{Q}{t}$.

Therefore the force F acting on the charge is:

$$F = BIL = B \times \frac{Q}{t} \times vt$$

Simplified:

$$F = BQv$$

Where:

F = force in N

B = magnetic flux density in T

Q = charge on the particle in C

v = velocity of the particle in ms^{-1}

Force on moving charges in a magnetic field

The force (F) on a charge (Q) moving with a speed (v) at an angle (θ) to a magnetic field of flux density (B) is calculated using:

$$F = BQv\ sin\theta$$

When the charge is moving at an $90°$ angle to the magnetic field:

$sin\theta = sin90° = 1\ldots$ so $\ldots\ F = BQv$

When the charge moves parallel to the magnetic field:

$sin\theta = sin0° = 0\ldots$ so $\ldots\ F = 0$

Note:

When the following conditions are met, the charge experiences no force:

- It is stationary (i.e. $\mathrm{v} = 0$ therefore $\mathrm{F} = 0$)
- It moves parallel to the field (i.e. $\theta = 0$ so $F = 0$)

Fleming's left-hand rule can be used to predict the force's direction, but keep in mind that the current direction is that of conventional current* (which is opposite to that of electron flow).

The force (F) acting on the moving charge is always perpendicular to the direction of motion.

*Conventional current assumes current flows from the positive to the negative terminal.

The circular path of charged particles in a magnetic field

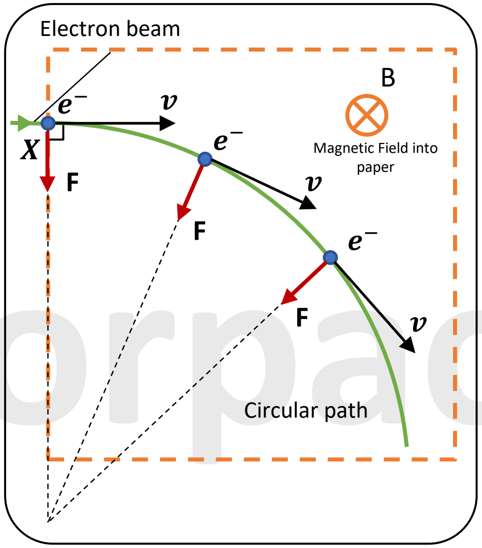
The effect of a magnetic field on moving electric charges can be demonstrated using an electron beam tube.

An 'electron gun,' which consists of a heated filament cathode and an anode, produces a fine beam of electrons. The electrons are accelerated towards and through the anode, which has a high positive potential in comparison to the cathode.

The electron beam then travels through a magnetic field (created by magnets or coils) that is perpendicular to the electron path.

When the beam passes over a fluorescent screen, the circular path taken by the beam may be seen. By reversing the magnetic field direction, the beam deflection can be reversed.

Fleming's Left Hand rule can be used to determine the direction of force acting on the electrons as they pass through a magnetic field.



To use Fleming's LH rule for charged particles, use your second finger (current) as the direction of motion, but because electrons have a negative charge, an electron beam moving to the right is viewed as conventional current moving to the left. So point your second finger in the opposite direction to its motion. Thus the force (F) acting on an electron at point X is downwards, deflecting the beam in that direction.

The force direction changes as the beam direction changes.

The force is always perpendicular to the motion direction.

tutorpacks.co.uk

Analysis of the circular path of charged particles in a magnetic field

The constant force $(F = BQv)$ exerted on a charged particle as it moves at right angles to an uniform magnetic field is perpendicular to both the particle motion and the field direction.

As a result, even if the force changes the particle's direction of motion continually, it has no effect on its speed (and hence on its kinetic energy).

Therefore the particle moves in a circular path while it is in the magnetic field.

Electromagnetic force*, which acts on the charged particle as a result of its interaction with the magnetic field, provides the centripetal force required for it to move in a circular path.

The diagram shows a particle of mass (m) and charge (Q) which moves with speed (v) in a perpendicularly directed magnetic field of flux density (B).

The particle moves in a circular path of radius (R) due to the magnetic force exerted on it. Therefore:

$$magnetic\ force = centripetal\ force$$

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

Simplified:

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

*The electromagnetic force is an interaction that occurs between electrically charged particle and is the combination of magnetic and electrical forces.

tutorpacks.co.uk

Analysis of the circular path of charged particles in a magnetic field

We can conclude the following from the equation for the radius (R) of the path:

- If m is increased, R increases (more mass – wider circle)
- If v is increased, R increases (faster speed – wider circle)
- If B is increased, R decreases (stronger field – tighter circle)
- If Q is increased, R decreases (greater charge – tighter circle)

The magnetic field on the particle does no work. Because the magnetic force acts at right angles to the motion of the particles.

Magnetic fields are used to control charged particle beams in:

- Old televisions and cathode ray tube,
- Mass spectrographs,
- High energy particle accelerators (cyclotron and synchrotron).

Analysis of the circular path of charged particles in a magnetic field

An object in circular motion has a frequency of rotation (f) equal to its velocity (v) divided by the distance it travels in each rotation $(2\pi r)$:

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

This can be used with the formula for r from the previous page to obtain an expression for rotation frequency in terms of $B, Q,$ and m:

$f = \frac{v}{2\pi r}$ and $r = \frac{mv}{BQ}$

Therefore:

$$f = \frac{v}{2\pi\left(\frac{mv}{BQ}\right)} = \frac{BQ}{2\pi m}$$

So the frequency of rotation of a charged particle in a magnetic field is unaffected by its velocity.

Only the magnetic flux density, mass, and charge determines how long it takes a particle to complete a full circle.

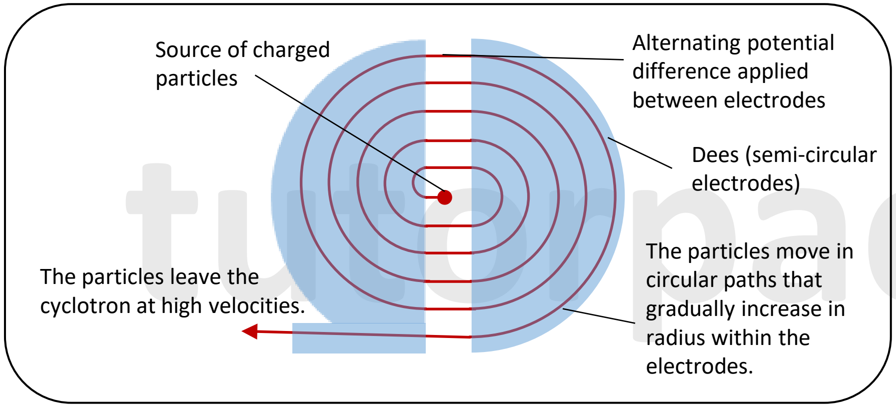
Increasing a particles velocity will travel a circular path with a larger radius, but it will take the same amount of time to complete it.

Cyclotron (AQA only)

In particle accelerators such as cyclotrons, the circular path of particles in a magnetic field is an effect that can be utilised.

Cyclotrons have a wide range of applications, e.g. in medicine. For radiotherapy, cyclotrons can be used to create radioactive tracers or high-energy beams of radiation in order to treat cancer. Cyclotrons can also be used to change the nuclear structure of an atom.

A cyclotron consists of two hollow semi-circular electrodes (sometimes known as "dees" due to their D-shape) with an uniform magnetic field applied perpendicularly to the electrodes' plane and an alternating potential difference applied between them.



Charged particles are created and shot in all directions from the source into one of the electrodes, where they follow an oval/circular path and eventually exit the electrode due to the magnetic field. An applied p.d. between the electrodes accelerate the particles across the gap until they enter the next electrode.

The direction of the p.d. will have been reversed when the particles enter the next electrode (i.e. the charge of the electrodes will switch so that the negative electrode will now be the positive electrode or vice versa, attracting the particle), and the particle will accelerate again before entering the next electrode. The process repeats as the particles spiral outwards, increasing in speed, before eventually exiting the cyclotron.

Cyclotron (AQA only)

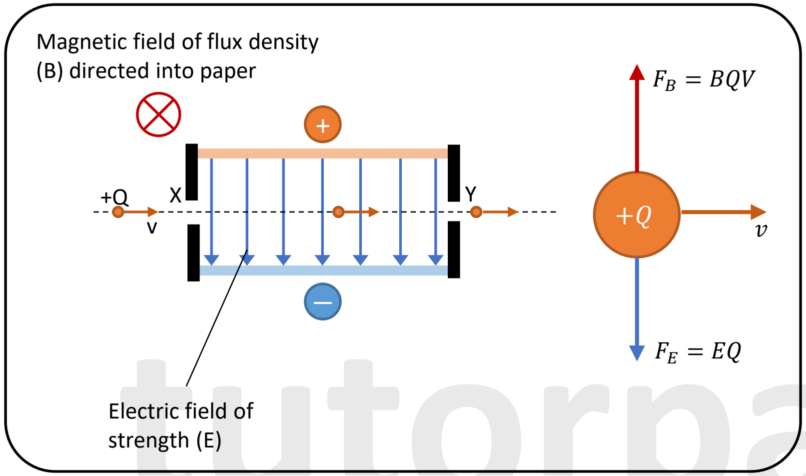
Because the particle's speed increases slightly each time it crosses the electrodes, it will follow a larger-radius circular path before exiting the electrode.

We need an alternating p.d. because if the p.d. wasn't alternating the particle would slow down after leaving the second electrode. As a result, every half turn, we'll have to reverse the polarity of the two electrodes.

The particles will always spend the same amount of time in each electrode or cross the gap at the same time since the frequency of circular motion is independent of radius. The alternating p.d. will have a constant frequency if $B, Q,$ and m are constant.

Motion of Charged Particles in Combined Electric and Magnetic Fields

A velocity selector is a device that uses combined electric and magnetic fields to only allow charged particles with a specific, chosen velocity to pass through it.



The diagram above shows a cross sectional view of a velocity selector. When charged particles enter the device, they pass through an area with a strong electric field (E) acting vertically downwards and a magnetic field of flux density (B) perpendicular to the electric field.

A particle with velocity (v) and charge (+Q) entering at (X) is subjected to opposing forces due to the two fields.

The electric field force ($F_E = EQ$) acts vertically downwards on the particle, while the magnetic field force ($F_B = BQv$) acts vertically upwards (Fleming's left-hand rule specifies this direction).

Motion of Charged Particles in Combined Electric and Magnetic Fields

In order for the particle to experience NO DEFLECTION and so exit the device at Y:

Magnetic force up = electric force down

$$\boldsymbol{BQv = EQ}$$

From which:

$$v = \frac{E}{B}$$

Where:

v = velocity of the particle in ms^{-1}

E = electric field strength in NC^{-1}

B = magnetic field of flux density in T

Remember:

- By controlling E and B, only particles of velocity, $v = \frac{E}{B}$ are allowed through.
- E and B can be used to calculate the velocity (v) of a charged particle.

If a charged particle beam with particles travelling at different speeds approaches the crossed-fields region:

For faster particles, $F_B = BQv$ will be greater and smaller for slower particles.

For particles of varying speeds, $F_E = EQ$ is constant.

Therefore, faster particles are deflected upwards because: $F_B > F_E$.

Slower particles are deflected downwards because: $F_B < F_E$.

Mass-Spectrometer

Mass spectrometers are used to accurately measure and identify the mass of charged particles. Although the exact construction of a mass spectrometer depends on the type of particle being studied, all mass spectrometers use a combination of electric and magnetic fields to control the motion of the particles under investigation. Some are made to analyse biological specimens (large molecules), while others are made to analyse atoms' isotopic composition.

The Bainbridge mass spectrometer, which can be used for isotopic analysis, is shown in the diagram below.

A velocity selector directs a narrow beam of positively charged particles (ions) in a vacuum. The beam passes through a region with a strong electric field E and a magnetic field with a flux density B_1 that is perpendicular to the electric field.

Particles with velocity $v = \frac{E}{B_1}$ will pass through undeflected. This velocity can be adjusted by controlling the size of E and B_1.

These particles then enter a uniform magnetic field of flux density B_2 and are caused to move in a circular path of radius R.

As the particle moves in a circular path due to the uniform magnetic field:

$$magnetic\ force = centripetal\ force$$

$$B_2Qv = \frac{mv^2}{R}$$

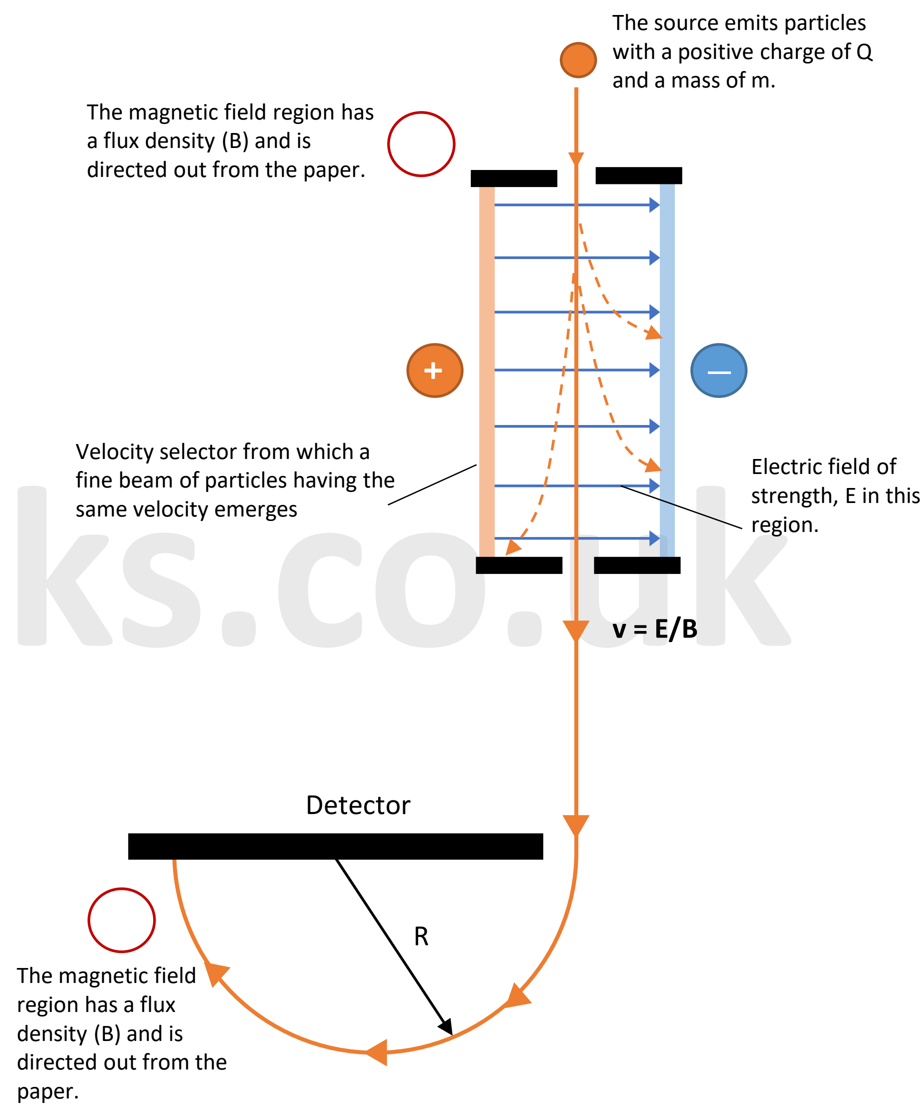
$$R = \frac{mv}{B_2Q}$$

From which:

$$R = \frac{mE}{QB_2B_1}$$

Therefore the mass m can be determined by measuring R.

Mass-Spectrometer



Please see '12.2.2 Motion of Charged Particles worked examples' pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.