



A2 Level Physics

Chapter 8 – Nuclear and Particle Physics

8.3.1 Particle Accelerators (Edexcel Only)

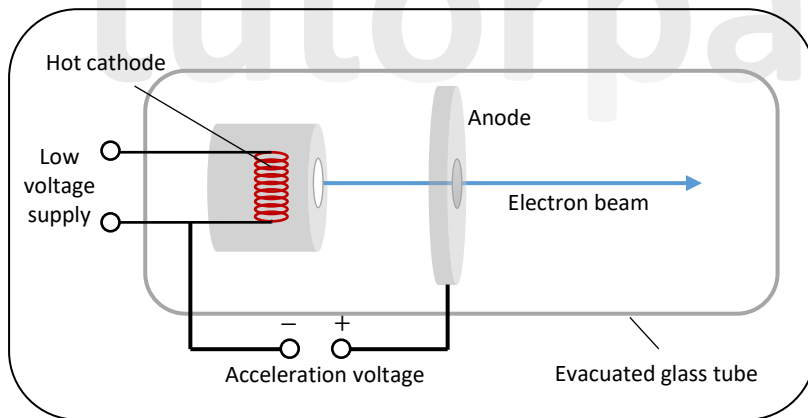
Notes

Thermionic Emission

Thermionic Emission occurs when a metal is heated to the point where the free electrons on its surface obtain enough energy to be emitted.

An electron gun uses thermionic emission by heating a cathode (negative electrode) to a point where electrons are emitted. The cathode is a filament which is connected to a low voltage supply, which causes the filament to heat up and emit those electrons. Keep in mind that the filament is the metal wire inside a light bulb that converts electrical energy into light (and heat).

A potential difference is also used by the electron gun to accelerate the electrons. So once the electrons are released from the hot cathode, they are accelerated towards the anode (positive electrode) which has a small gap. The electrons that pass through this gap form a narrow electron beam that travels past the anode at a constant velocity.



Thermionic Emission

Electrons (or charges) can be accelerated using electric fields in order to increase their velocity, but they can also be accelerated radially using magnetic fields, because the force experienced by an electron moving in a magnetic field is always perpendicular to its motion.



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:

$$F = BQv$$

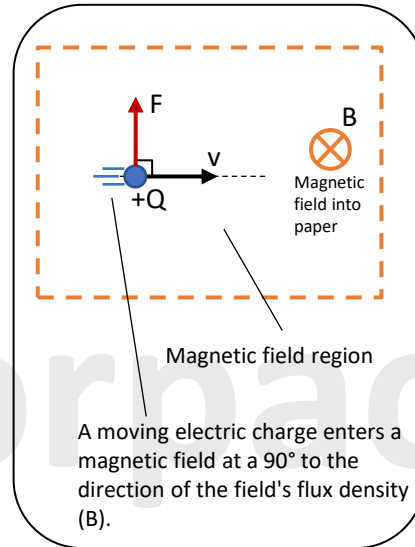
Where:

F = force in N

B = magnetic flux density in T

Q = charge on the particle in C

v = velocity of the particle in $m s^{-1}$



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:

$$\sin\theta = \sin 90^\circ = 1 \dots \text{so} \dots F = BQv$$

When the charge moves parallel to the magnetic field:

$$\sin\theta = \sin 0^\circ = 0 \dots \text{so} \dots F = 0$$

Note:

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

- It is stationary (i.e. $v = 0$ therefore $F = 0$)
- 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

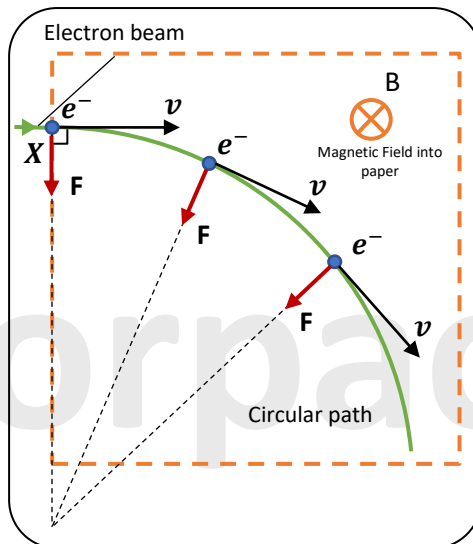
The effect of a magnetic field on moving electric charges can be demonstrated using an electron beam tube.

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.

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:

$$\text{magnetic force} = \text{centripetal force}$$

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

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.



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 :

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

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.



Particle Accelerators

Scientists collide nucleons (protons and neutrons) with other particles at extremely high speeds (very high energies) in order to study their internal substructure.

High-energy particles are required because lower-energy particles just bounce off each other, keeping their internal structure intact.

If we can collide particles together hard enough, they will break up, revealing their structure.

Most of the time, additional particles are created from the energy of the collision. These additional particles can sometimes reveal or confirm new physics.

Accelerating particles to high enough speeds has been a challenge for scientists. You need to know the following two types of particle accelerators:

- Linear accelerator (LINAC) – uses an alternating electric field.
- Cyclotron – uses a magnetic field and an alternating electric field.

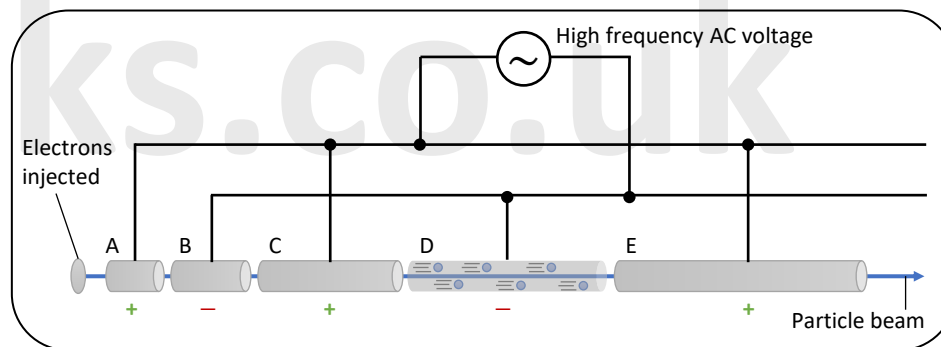
Linear Accelerator

Accelerating a beam of charged particles along a straight path is one of the simplest ways to generate energy high enough for these particle collisions. However, this is limited by the maximum achievable potential difference.

Therefore, the particles are accelerated in stages in order to overcome this problem. They are repeatedly accelerated through the maximum p.d., making the particles energies very high.

In order to accelerate electrons through the linear accelerator, electron guns are used to produce electron beams of relatively low-energy to be used in particle accelerators.

The electrons move in a straight line once inside the cylinder because the electrodes are equally attracting in all directions.



The alternating voltage supply is made to change as the electrons reach the centre of tube A. So, tube A will be positive at first pulling in the electron. As soon as the electrons reach the halfway point, tube A becomes negative which repels the electrons out of the end of tube A. But while tube A is now negative, tube B becomes positive. This not only draws the electrons as they exit tube A, but it also causes them to accelerate toward tube B.



Linear Accelerator

This process of alternating between positive and negative tubes caused by the AC voltage keeps repeating itself until the electrons reach the end of the line. Here the electrons have enough energy to emerge and collide with a target.

To keep the particles (which are moving faster and faster) accelerating, the acceleration tubes must increase in length as the particles travel through each successive one at a higher speed, whilst the time between p.d. flips is fixed due to the alternating voltage having a uniform frequency. This ensures that the electrons have enough time inside the tubes to be accelerated again.

The usage of this type of accelerator is limited by how long you can afford to build it, keeping in mind that it must be completely contained in a vacuum to prevent particles from colliding with air atoms, and it must be perfectly straight. Scientists struggled to make longer linear accelerators, so they invented a cyclotron (a circular accelerator) to allow particles to be accelerated in an electric field repeatedly in a smaller region.

Linear Accelerator

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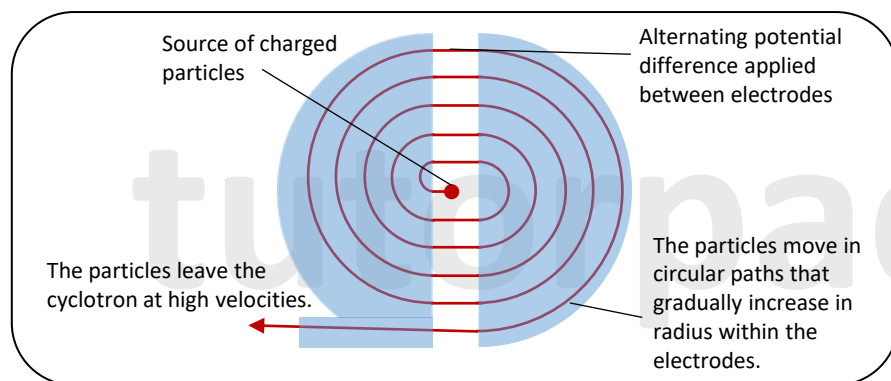


Cyclotron

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 a 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 accelerates 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

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.

Note:

- 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.
- Cyclotrons have a wide range of applications, including medicine. For use in radiotherapy, cyclotrons can create radioactive tracers or high-energy beams of radiation.

Cyclotron

Cyclotron Frequency

In order to maintain the acceleration at exactly the correct moment, the p.d. must change direction exactly when the particles exit from one dee to move across the gap to the other dee. This implies the voltage supply must have a square wave pattern with immediate polarity flipping.

The frequency of these polarity switches is solely determined by the particle and the strength of the applied magnetic field.

To calculate this frequency we know:

$$f = \frac{1}{T}$$

And

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

During one complete period of the alternating voltage the particle will pass through both dees, thus completing a full circle at that radius.

However the radius is equal to:

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

Therefore T becomes:

$$T = \frac{2\pi mv}{Bqv}$$
$$T = \frac{2\pi m}{Bq}$$

And so: $f = \frac{Bq}{2\pi m}$

As a result, the frequency required is independent of the radius, meaning that a constant frequency can be used while the particle completes each semicircle through a dee in the same time. That is, until the speed becomes so fast that mass changes through relativistic effects.

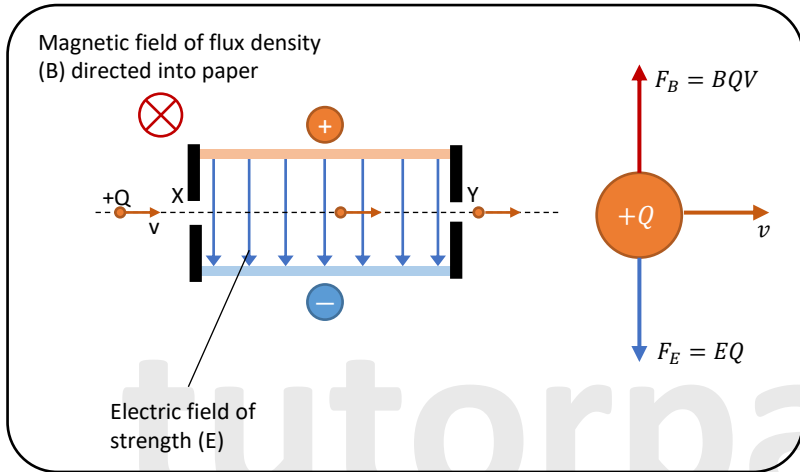


Cyclotron

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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:

$$\text{Magnetic force up} = \text{electric force down}$$

$$BQv = EQ$$

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

$$B_2 Q v = \frac{m v^2}{R}$$

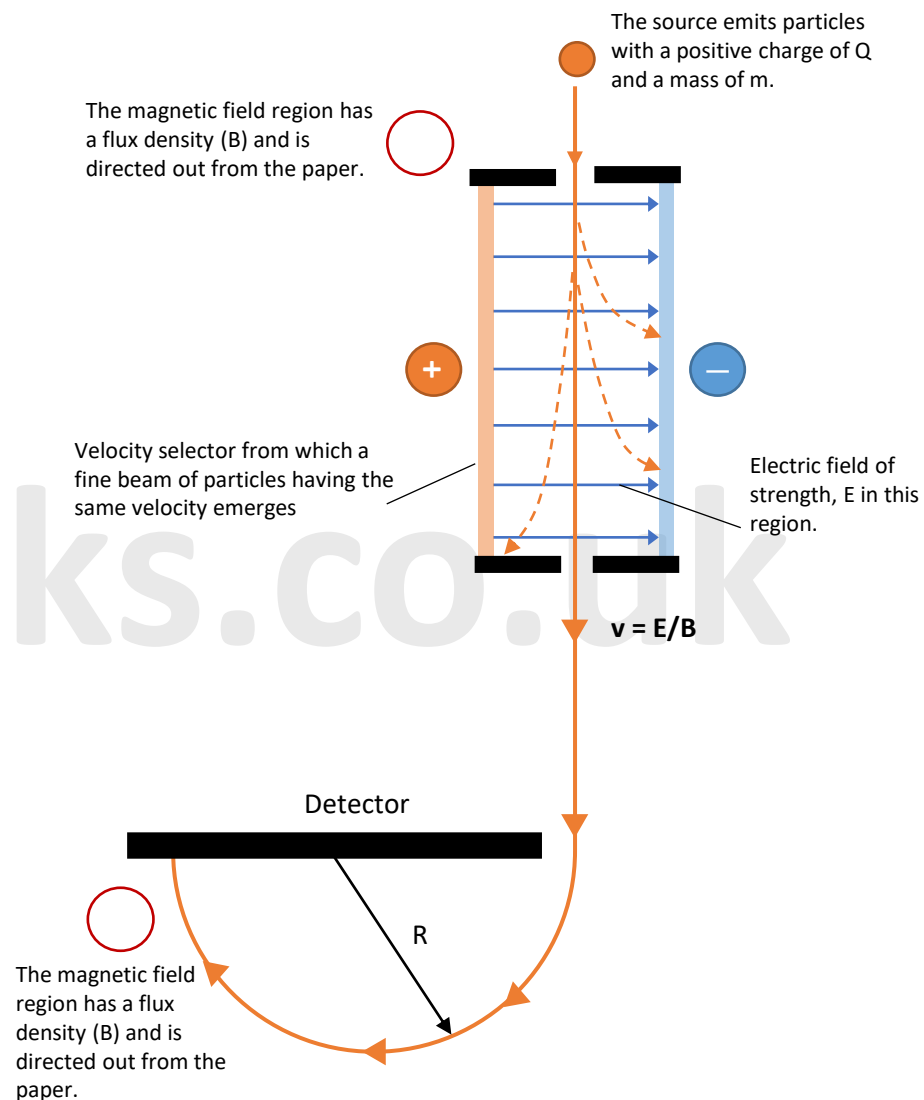
$$R = \frac{m v}{B_2 Q}$$

From which:

$$R = \frac{m E}{Q B_2 B_1}$$

Therefore the mass m can be determined by measuring R .

Mass-Spectrometer



Please see **'8.3.2 Particle Accelerators worked examples'** pack for exam style questions.

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

