Special relativity

In 1905, Albert Einstein (Figure 1.48) published a paper which included a theory that is now called **special relativity***. In his paper, Einstein extended the Principle of relativity to show that the laws of physics, not just the laws of motion and mechanics, were the same in all inertial reference frames.

Figure 1.48: Albert Einstein

Einstein used a famous experiment performed by Michael Faraday to extend the Principle of relativity to include the laws of electricity and magnetism.

Example 1.28

Faraday showed that an electric current was produced when a magnet was moved into a coil of wire, and this is known as Faraday's law of induction (described in Chapter 2.5). Einstein showed that Faraday's Law was the same in two inertial reference frames (Figure 1.49). When the magnet is moved at constant velocity into the stationary coil, a current is produced. When the coil is moved at constant velocity into a stationary magnet, the same current is produced which is evidence that the laws of physics, in this case, the law of induction, is the same on both inertial reference frames.

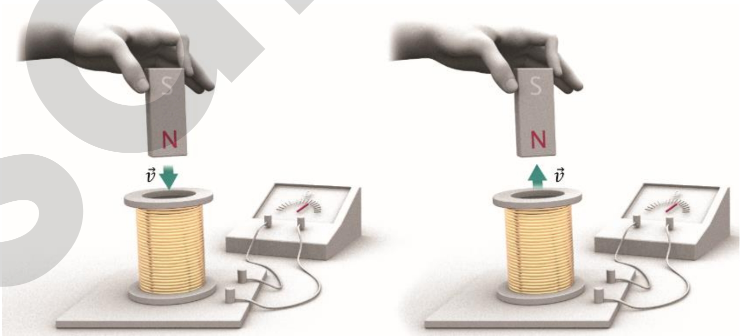


Figure 1.49: Faraday's Law in different reference frames.

Einstein realised that if the laws of electricity and magnetism were the same in all inertial reference frames, then the speed of electromagnetic waves must be the same in all inertial reference frames. Einstein included two postulates in his theory of special relativity

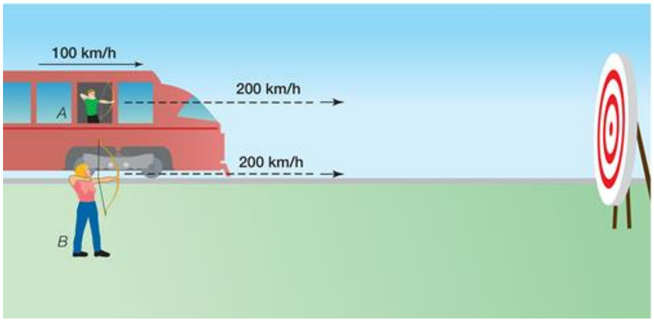
(1) The laws of physics are the same in all inertial reference frames.
(2) The speed of light is an absolute constant and is the same in all inertial reference frames.

The term "special" is used as the predictions of Einstein's theory are limited to observers in inertial reference frames.

Question

The diagram below shows two observer's firing arrows.

Observer A moves at a constant velocity to the right, and Observer B is at rest.



Both arrows travel towards a target that is equidistant from the two observers.

(a) Identify the arrow that hits the target first and give a reason.

____

____________________________________ (2 marks) **KA2**

(b) Einstein postulated that the laws of physics are the same in all inertial reference frames.

(1) Define an inertial reference frame.

____________________________________ (1 mark) **KA1**

(2) Explain this postulate with reference to the example in the diagram above.

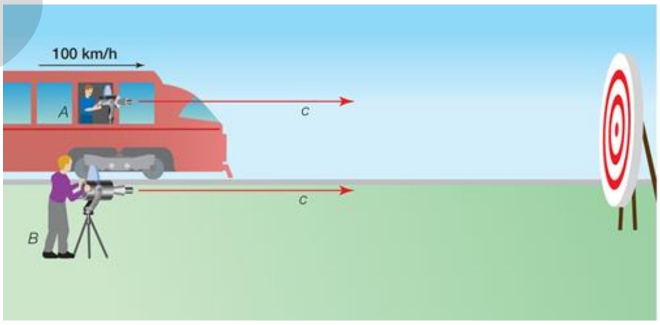
____

____

____

____________________________________ (2 marks) **KA1**

(c) The two observers then simultaneously emit a pulse of light in the direction of the target.



Identify the light pulse, A or B, reaches the target first and give a reason.

____

____________________________________ (2 marks) **KA2**

Two events that appear simultaneous for a stationary observer may not be for an observer in motion.

The term **simultaneous** refers to events that occur at the same time. Einstein's Theory of Special Relativity states that events that are simultaneous in one reference frame are not simultaneous in a reference frame that is moving relative to an observer.

Example 1.29

A spacecraft is travelling uniformly at a speed of $0.7c$ when a crew member turns on a light positioned in the centre of the cabin. The crew member inside the spacecraft observes the light waves reach the front and rear of the cabin simultaneously in their reference frame (Figure 1.50).

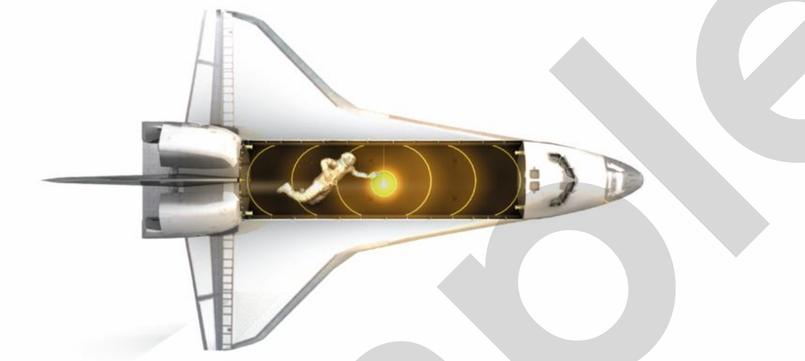


Figure 1.50: Light waves viewed by observers inside the cabin.

An astronomer at rest on Earth is watching the spacecraft through a powerful telescope and observes the crew member turn on the light in the centre of the cabin. The astronomer observes the light waves reach the rear of the cabin first in their reference frame as the rear of the cabin has moved closer to the centre of the cabin since the light was turned on (Figure 1.51).

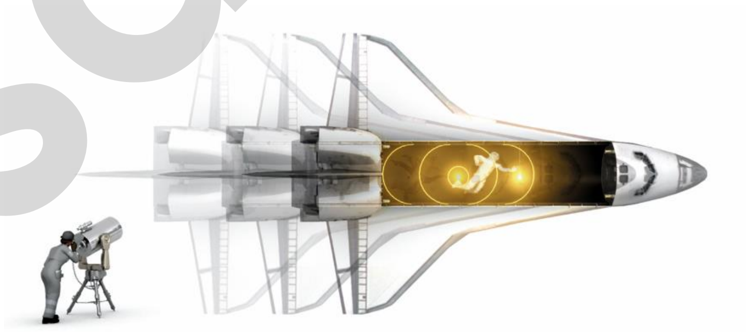


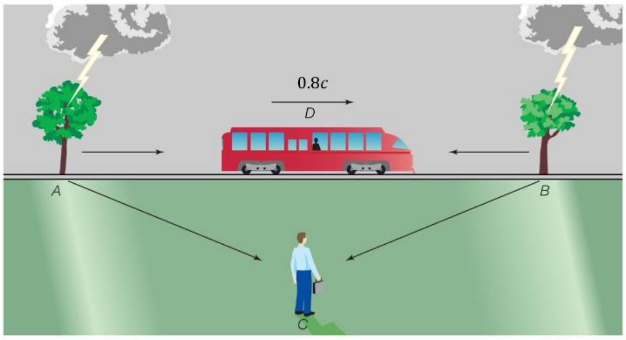
Figure 1.51: Light waves viewed by an astronomer on Earth.

To the astronomer on Earth, the light waves reach the front and rear of the cabin at different times showing that the two events are not simultaneous when the spacecraft moves relatively to the astronomer at speed $0.7c$. This thought experiment shows that events that are simultaneous in one reference frame are not simultaneous in a reference frame that is moving relative to an observer.

Question

The diagram below shows a fictional vehicle moving uniformly at $0.8c$ between two trees, A and B

Lightning strikes trees A and B and the flashes of light move towards two observers C and D.



Observer C is at rest in a position that is equidistant from trees A and B.

(a) Identify and explain which flash of light is seen first in the reference frame of Observer C.

(2 marks) **KA2**

(b) Identify and explain which flash of light is seen first by Observer D in the reference frame of Observer C.

(2 marks) **KA2**

(c) Draw one conclusion about the simultaneity of events from this example.

(1 mark) **KA2**

(d) Observer D turns on a light in the centre of the vehicle and sees the waves of light reach the front and rear of the cabin simultaneously in their reference frame.

Describe and explain the same event in the reference frame of Observer C.

(2 marks) **KA2**

Lorentz factor

The Lorentz factor (γ) is named for the Dutch theoretical physicist Hendrik Lorentz (Figure 1.55).

Figure 1.55: Hendrik Lorentz (1853–1928).

In the 1890s, Lorentz developed a concept known as length contraction that Einstein used to develop the Theory of Special Relativity. In the context of time dilation, the Lorentz factor is equal to the ratio of the time interval in the stationary observer's reference frame (t) to the time interval in the moving reference frame (t_0).

$$\gamma = \frac{t}{t_0}$$

The minimum value of the Lorentz factor is one, and this occurs when the time intervals measured in the stationary and moving reference frames are equal. The Lorentz factor increases with the relative velocity of the two reference frames, as shown in Figure 1.56.

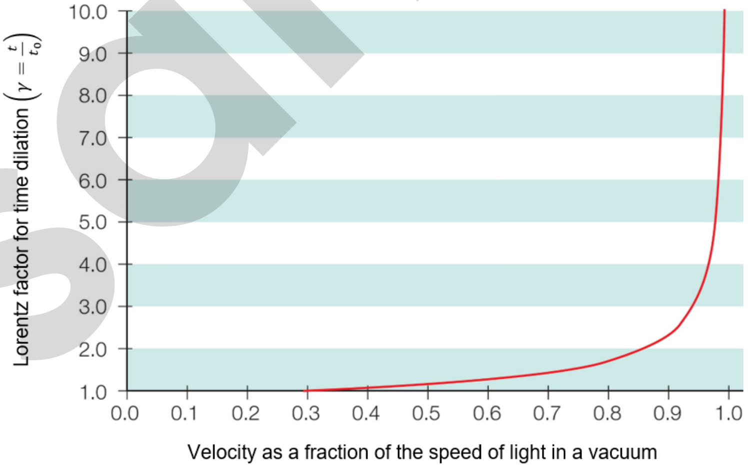


Figure 1.56: The effect of relative velocity on the Lorentz factor for time dilation.

Figure 1.56 shows that the effects of time dilation only become significant when the moving object has a velocity greater than $0.3c$, which is 0.9×10^8 m s^{-1}. Objects with velocities greater than $0.3c$ are described as moving at **relativistic speeds** as the effects of special relativity such as time dilation become more significant when measured. Very few material objects studied move at relativistic speeds except for subatomic particles.

Question

The diagram below shows an illustration of theoretical spacecraft that could achieve speeds of $0.8c$.

(a) At this velocity, a stationary observer on Earth would measure the time taken for the spacecraft to travel from Earth to Uranus as 216 minutes.

Calculate the time taken in the reference frame of a passenger aboard the spacecraft.

(2 marks) **KA2**

(b) Calculate the Lorentz factor in this example.

(2 marks) **KA2**

Question

A superhero travelling at $0.99c$ traverses the solar system in 269 hours in their reference frame.

(a) Calculate the time interval measured in the reference frame of a stationary observer who monitors the superhero from Earth.

(2 marks) **KA2**

(c) Calculate the Lorentz factor in this example.

(2 marks) **KA2**

Example 1.36

Electrons ($m_0 = 9.11 \times 10^{-31}$ kg) are accelerated to 0.999c in a particle accelerator.

The relativistic momentum of the electrons is calculated below.

$$p = \frac{1}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}} \times m_0 v$$

$$p = \frac{1}{\sqrt{\left(1 - \frac{(0.999 \times 3 \times 10^8)^2}{(3 \times 10^8)^2}\right)}} \times 9.11 \times 10^{-31} \times 0.999 \times 3 \times 10^8$$

$$p = 6.11 \times 10^{-21} \text{ kg m s}^{-1}$$

When v is much smaller than c, the relativistic momentum is approximately equal to the classical momentum. However, when v approaches c, the momentum approaches infinity. Figure 1.60 shows the momentum as a function of speed. The graph shows that the predictions of classical momentum are incorrect as the momentum of a particle only becomes infinite after its speed becomes infinite.

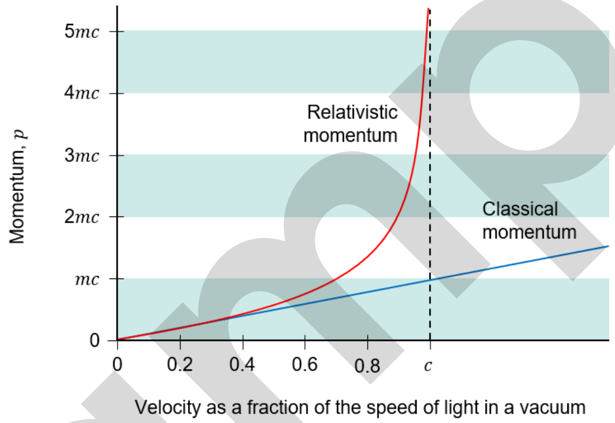


Figure 1.60: The contradictory predictions of relativistic and classical momentum

In the context of momentum, the Lorentz factor provides a measure of the amount by which relativistic momentum of a particle differs from its classical momentum. When v is much smaller than c, the Lorentz factor is approximately equal to one meaning that the relativistic momentum is approximately equal to the classical momentum. However, when v is almost as large as c, the Lorentz factor approaches infinity. Figure 1.61 shows how γ increases as v approaches c.

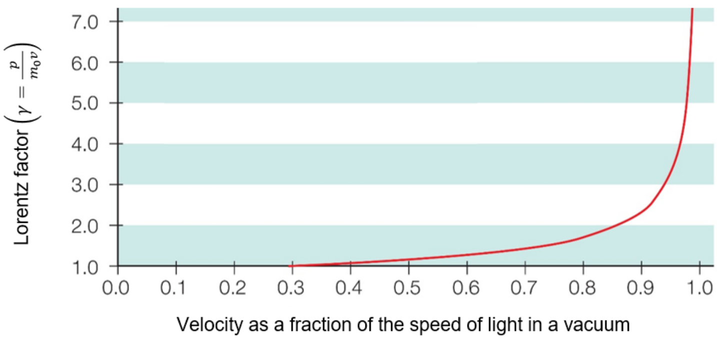


Figure 1.61: The effect of relative velocity on the Lorentz factor for momentum.

The cosmic speed limit

Figure 1.60 shows that the momentum of a particle moving at relativistic speeds is no longer directly proportional to its velocity because the Lorentz factor approaches infinity as the particle speed increases (Figure 1.61). This has a significant consequence for the relationship between momentum and force. Newton's Second Law states force is equal to the rate of change in momentum.

$$F = \frac{\Delta p}{\Delta t}$$

Experiments show that this relationship is still valid for particles moving at high speeds if the relativistic momentum is used rather than the classical momentum. However, because momentum is no longer directly proportional to velocity, the rate of change of momentum is no longer directly proportional to acceleration. As a result, a constant force does not cause constant acceleration when a particle moves at relativistic speeds. It is found that if the constant force and velocity have the same direction, the relationship is given by the formula below:

$$F = \frac{ma}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{3}{2}}} = \gamma^3 ma$$

The formula above shows that the acceleration (a) caused by the constant force (F) is inversely proportional to the cube of the Lorentz factor (γ^3). Therefore, since the Lorentz factor increases with particle speed, the acceleration caused by a constant force decreases as particle speed increases. This means that the ability of the particle to be accelerated, called inertia, decreases as particle speed increases. As the particle speed approaches c, the momentum approaches infinity, and the acceleration approaches zero, no matter how large the applied force. Furthermore, acceleration becomes zero when particle speed is equal to c, which shows that speed cannot increase further when a particle reaches c. The speed of light is sometimes called the **cosmic speed limit** as no particle, or material object can travel faster than light.

Another way of expressing this concept is to state that a force cannot accelerate a particle to a speed higher than c because the particle's momentum becomes infinitely large as the speed approaches c. The amount of additional force required for each additional increment of velocity becomes larger and larger until no amount of force can raise the velocity any higher. This prediction of relativity is illustrated in graphs (a) and (b) in Figure 1.62.

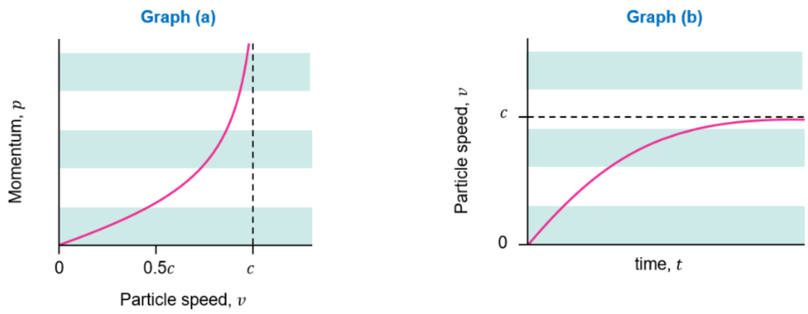


Figure 1.62: Predictions of special relativity on momentum and particle speed.

2.1: Electric fields

Electrostatically charged objects exert forces upon one another; the magnitude of these forces can be calculated using Coulomb's Law.

- Solve problems involving the use of $F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
- Using proportionality, discuss changes in the magnitude of the force on each of the charges as a result of a change in one or both of the charges and/or a change in the distance between them.
- Explain that the electric forces are consistent with Newton's Third Law.

Electric charge is a property of some particles and objects. Electrically charged particles and objects have either a positive or negative charge and exert mutual electrostatic forces on one another that are consistent with Newton's Third Law. Like charges exert mutual repulsive forces on one another, and opposite charges exert mutual attractive forces on one another as depicted in Figure 2.01.

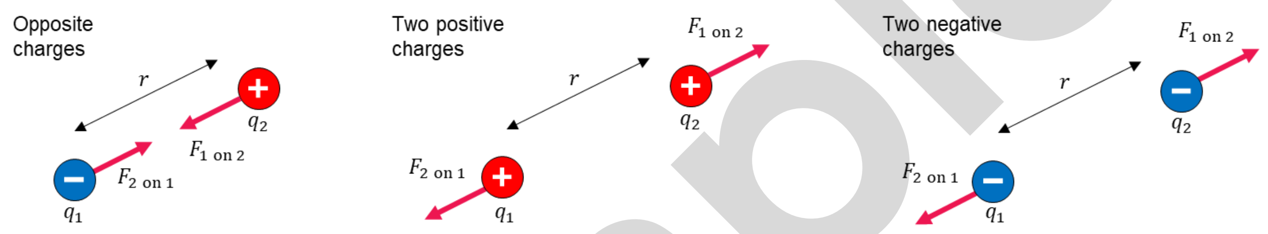


Figure 2.01: Electrostatic forces between charges.

Between 1785 and 1789, French physicist Charles-Augustin de Coulomb (Figure 2.02) conducted a series of precise experiments on electric charges and determined that the electrostatic force between charges was directly proportional to the product of the two charges and inversely proportional to the square of the distance between them. This is known as **Coulomb's Law**.

Formula	$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$	
Symbol	Variable	SI unit
F	Electrostatic force	N
q_1	Charge of particle or object 1	C
q_2	Charge of particle or object 2	C
r	Distance between the particles or objects	m
$\frac{1}{4\pi\varepsilon_0}$	Coulomb's Law constant	$N\ m^2\ C^{-2}$

Figure 2.02

Coulomb derived a constant of proportionality known as the **Coulomb's Law constant.** The constant has a magnitude of 9.00 x 10^9 N m^2 C^{-2} and features the physical constant ε_0 commonly called the **permittivity of free space** which is a factor that affects the magnitude and propagation of the electric field between two charges.

Electric dipole

An **electric dipole** consists of two point charges separated by a short distance with each being affected by the electric field of the other charge. Figure 2.04 shows the electric field surrounding a dipole composed of oppositely charged point charges. In addition, a photograph has been added showing the electric field of a dipole using pepper grains, cooking oil and two oppositely charged electrodes of equal magnitude. The pepper grains align along the electric field lines which are curved and directed from the positive charge to the negative charge. The direction of the electric field at any point is tangent to the field line as shown by the vector arrow at point P.

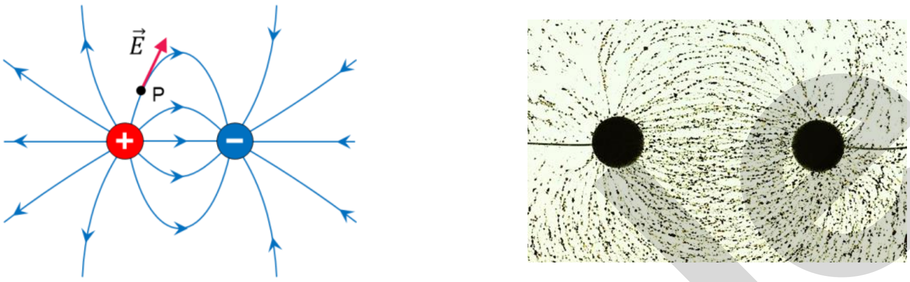


Figure 2.04: Electric field surrounding a dipole composed of opposite charges.

Figure 2.05 shows the electric field surrounding a dipole composed of two positive charges. The diagram shows that electric field lines diverge in the area between the two point charges.

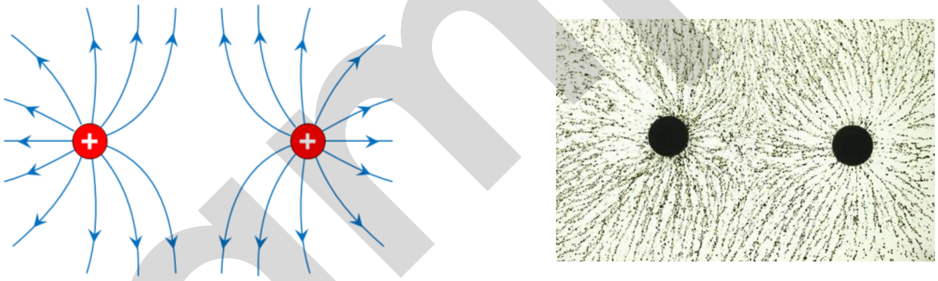


Figure 2.05: Electric field surrounding a dipole composed of like charges.

Oppositely charged parallel plates

Figure 2.06 shows the electric field between and near the edges of two finite oppositely charged parallel plates. The field lines are perpendicular to the surface of the metal plates. Furthermore, the field lines are parallel and evenly spaced in the region between the plates where the field is uniform and are curved near the edges, indicating a non-uniform field outside the plates.

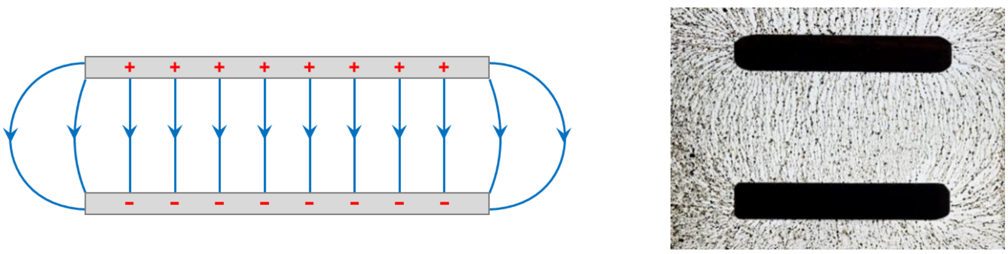


Figure 2.06: Electric field between two oppositely charged parallel plates.

There is no electric field inside a hollow conductor of any shape, provided that there is no charge in the cavity.

- Sketch the electric field produced by a hollow spherical charged conductor.

An electrical conductor is a solid or hollow object that contains free-moving electric charges. Any excess charge spreads out evenly across the surface of a conductor and the charges reach a state of **electrostatic equilibrium** where they are stationary and evenly separated to minimise electrostatic repulsion. The electric field due to the stationary surface charges is perpendicular to the surface of the conductor as depicted in Figure 2.07.

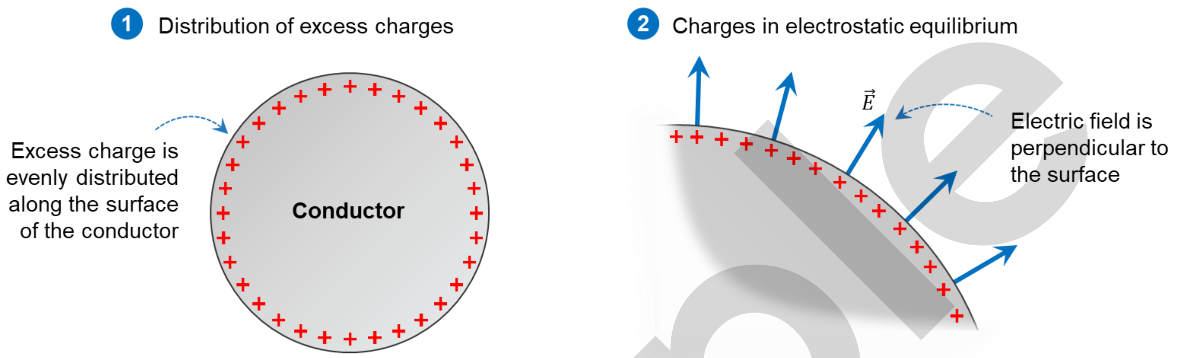


Figure 2.07: Distribution of excess charges along the surface of the conductor.

Hollow conductors

A **hollow conductor** is an electrical conductor containing an empty cavity. There is no electric field inside a hollow conductor of any shape, provided that there is no charge in the cavity. If there were an electric field inside the hollow cavity, this field would propagate outwards from the cavity and pass through the surface of the conductor. The field would exert a force on the charges at the surface of the conductor and cause them to accelerate. The observation that the surface charges are in electrostatic equilibrium is evidence that there is no electric field inside a hollow conductor.

When sketching the electric field of a hollow spherical charged conductor, it is essential to draw the field lines evenly spaced and perpendicular to the surface at any point. No field lines are drawn inside the hollow cavity as there is no electric field inside the cavity, as shown in Figure 2.08.

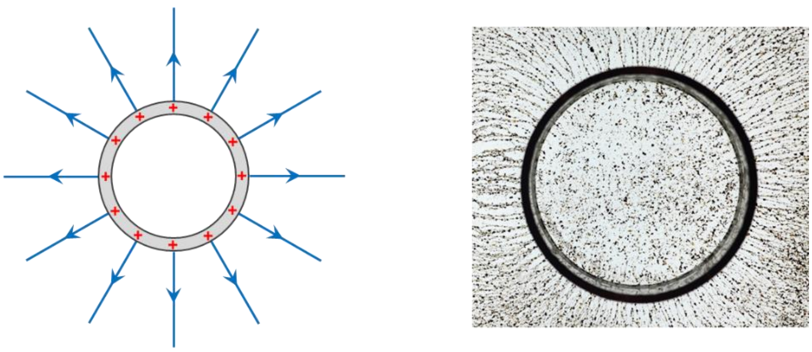


Figure 2.08: Electric field surrounding a hollow ring conductor.

2.2: Motion of charged particles in electric fields

When a charged body moves or is moved from one point to another in an electric field, work is done on or by the field.

- The electric potential difference between two points is the work done per unit charge on a small positive test charge moved between the points, provided that all other charges remain undisturbed.
- Solve problems involving the use of $W = q\Delta V$

Electric charges have **electric potential energy** due to their position in an electric field. Electric potential energy is the electrical analogue of gravitational potential energy, and its magnitude is the product of the electrostatic force due to the field (Eq) and the distance (d) from the position where the electric potential energy is zero. The electric potential energy of a charge changes when it moves or is moved between two positions in an electric field.

Figure 2.11 shows test charges* in uniform electric fields between two oppositely charged parallel plates. The electric potential energy of the charge is zero when it is in contact with the oppositely-charged plate. Work is done in moving the charge away from the oppositely-charged plate as energy must be transferred to overcome the electrostatic force that attracts the charge to the plate. Conversely, the electric potential energy of the charge decreases as it moves back towards the oppositely-charged plate in the direction of the electrostatic force. The decrease in electric potential energy can be understood using the Law of Conservation of energy. The electric potential energy is transformed to kinetic energy as the charge accelerates towards the oppositely-charged plate.

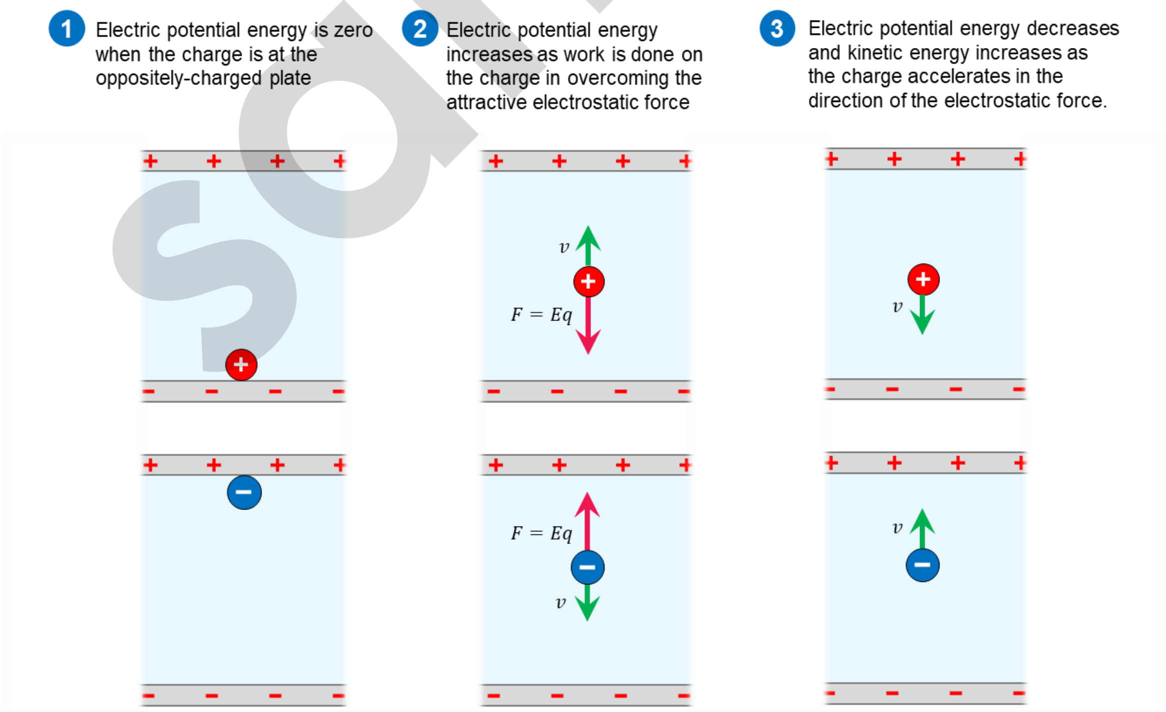


Figure 2.11: Change in electric potential energy of a positive charge in an electric field.

*A test charge is a point charge with a magnitude so small that it has a negligible effect on the electric field.

Electrostatic force

The electrostatic force on a charged particle moving in a uniform electric field is constant in magnitude and direction. The electrostatic force causes the charge to move with uniform acceleration in the direction of the positive or negative plate depending on its sign of charge. The magnitude of the acceleration is calculated using the formula derived below.

$$\begin{aligned} \vec{F} &= \vec{E}q \\ m\vec{a} &= \vec{E}q \\ \vec{a} &= \frac{\vec{E}q}{m} \end{aligned}$$

Example 2.17

A proton accelerated through an electric field which has a constant magnitude of 5 MV m^{-1}

Calculate the magnitude of the constant acceleration of the proton in the electric field.

$$\begin{aligned} \vec{a} &= \frac{\vec{E}q}{m} \\ \vec{a} &= \frac{5 \text{ x } 10^{6} \text{ x } 1.6 \text{ x } 10^{-19}}{1.673 \text{ x } 10^{-27}} \\ \vec{a} &= 4.8 \text{ x } 10^{14} \text{ m s}^{-2} \end{aligned}$$

The motion of charges in a uniform electric field

A charge has constant acceleration in the uniform electric field between oppositely charged parallel conducting plates, and its motion is described using the equations of motion with constant acceleration. When using the equations of motion, it is important to consider the direction of motion of the charge. Motion **parallel** to the electric field does not require a coordinate system as the vector quantities of velocity, displacement and acceleration are in the same direction. However, motion **antiparallel** to the electric field requires a coordinate system as the velocity and displacement are in the opposite direction to the acceleration. Figure 2.13 shows the motion of a positive charge parallel and antiparallel to the electric field.

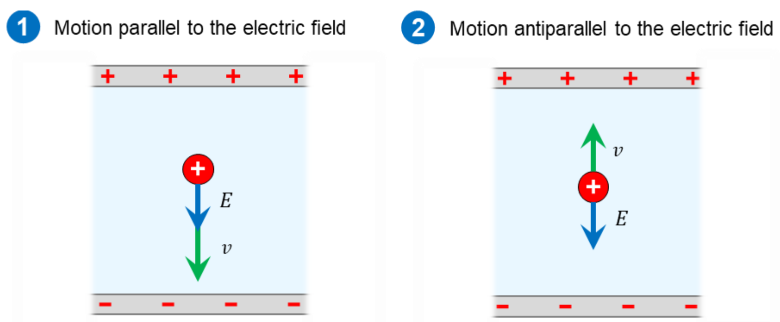
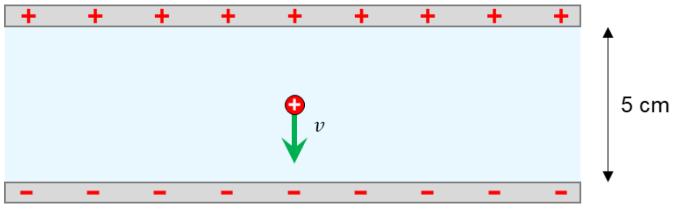


Figure 2.13: Motion of a positive charge parallel and antiparallel to a uniform electric field

Example 2.18

A proton enters a uniform electric field midway between two parallel plates.



1. Calculate the electric field strength if the potential difference between the plates is 500 V.

$$E = \frac{\Delta V}{d}$$
$$E = \frac{500}{0.05}$$
$$E = 1 \text{ x } 10^{4} \; V \text{ m}^{-1}$$

2. Calculate the magnitude of the acceleration of the proton.

$$\vec{a} = \frac{\vec{E}q}{m}$$
$$\vec{a} = \frac{1 \text{ x } 10^{4} \text{ x } 1.6 \text{ x } 10^{-19}}{1.673 \text{ x } 10^{-27}}$$
$$\vec{a} = 9.6 \text{ x } 10^{11} \text{ m s}^{-2}$$

3. Calculate the time taken for the proton to reach the negative plate.

$$s_V = v_{0_V} t + \frac{1}{2} a_V t^2$$
$$s_V = \frac{1}{2} a_V t^2$$
$$t = \sqrt{\frac{2 s_V}{a_V}}$$
$$t = \sqrt{\frac{2 \text{ x } 0.025}{9.6 \text{ x } 10^{11}}}$$
$$t = 2.3 \text{ x } 10^{-7} \text{ s}$$

4. Calculate the vertical component of velocity of the proton when it reaches the negative plate.

$$v_V = v_{0_V} + a_V t$$
$$v_V = 0 + (9.6 \text{ x } 10^{11} \text{ x } 2.3 \text{ x } 10^{-7})$$
$$v_V = 2.2 \text{ x } 10^{5} \text{ m s}^{-1}$$

Magnetic fields

Magnetism is a property of moving charges such as those found in permanent magnets and electric currents. A moving electric charge produces a **magnetic field** in the space that surrounds itself. Figure 2.19 shows the magnetic field surrounding a bar magnet.

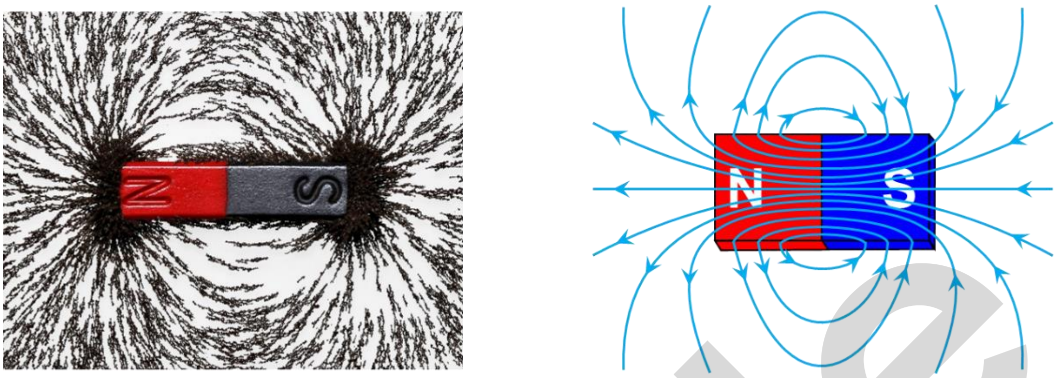


Figure 2.19: Magnetic field of a bar magnet.

Magnetic fields are represented using magnetic field lines. The magnetic field lines represent both the magnitude and direction of the field at a given point in the magnetic field. The direction of the magnetic field at any point in the field is tangent to the magnetic field line at that point and is determined using a small compass—the north pole needle of the compass points in the direction of the south pole of the magnet. The strength of the magnetic field at any point is represented by the number of magnetic field lines per unit area. The magnetic field is stronger where the field lines are closer together and weaker where the field lines are further apart. Figure 2.20 illustrates some important properties of magnetic fields.

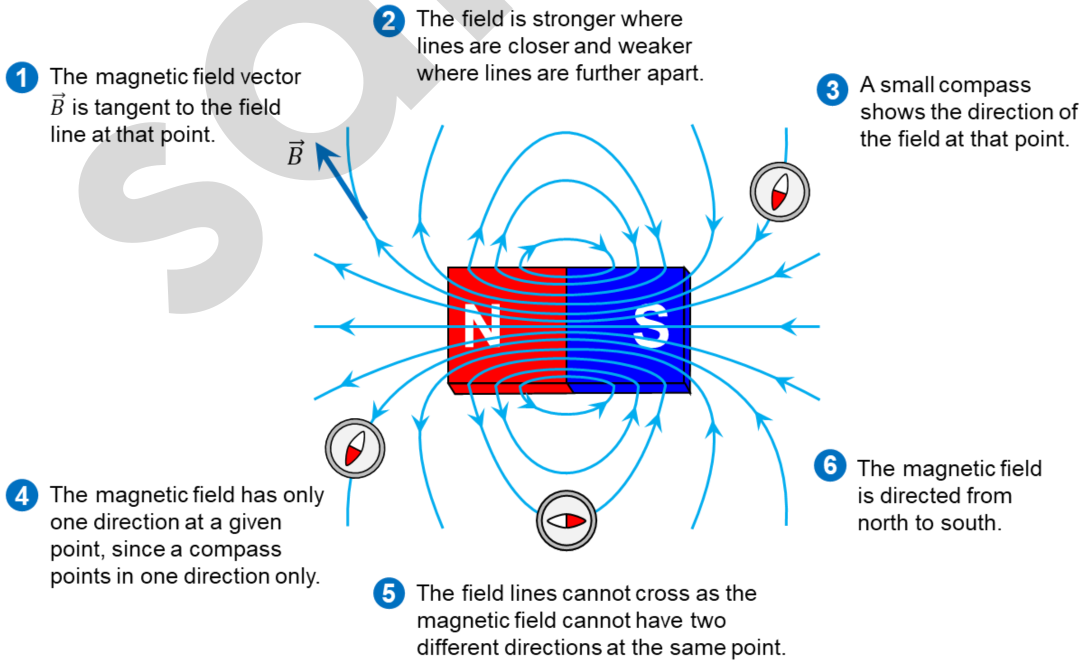


Figure 2.20: Some important properties of magnetic fields.

Current-carrying conductors

Electric current (*I*) is the flow of electric charge through a conductor. Electric current is a vector quantity, and its direction through a conductor is represented using **dot and cross notation** in which a dot represents a vector directed towards the observer, and a cross represents a vector directed away from the observer. In the context of electric current, a dot represents a current directed out of the page and a cross represents a current directed into the page. An electric current produces a magnetic field in the space surrounding the conductor. The shape of the magnetic field depends on the type of conductor. Figure 2.21 shows the magnetic fields produced by electric current flowing in a **straight conductor,** a **loop**, and a **solenoid** which is a series of loops placed along a common axis.

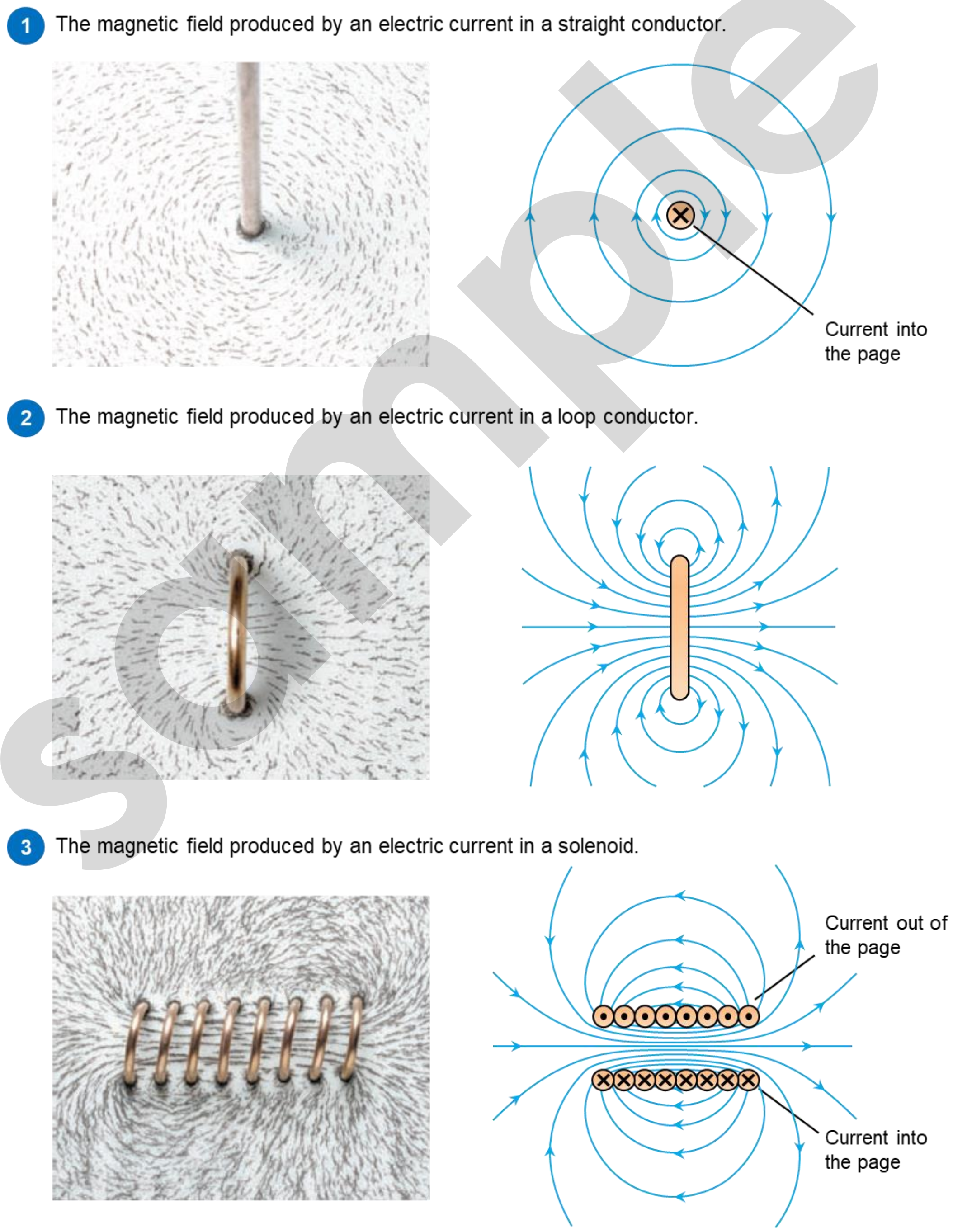


Figure 2.21: Magnetic fields surrounding a straight conductor, a loop, and a solenoid.

The magnitude of the magnetic field strength, B, at a radial distance, r, from the centre of a current-carrying conductor is given by $B = \frac{\mu_0 I}{2\pi r}$, where $\frac{\mu_0}{2\pi}$ = 2.00 x 10^{-7} T m A^{-1}

- Solve problems involving the use of $B = \frac{\mu_0 I}{2\pi r}$

Magnetic field strength is a measure of the magnetic force acting on a moving charge or electric current. Magnetic field strength is a vector quantity, and the SI unit is the **tesla**, named for the Serbian-American physicist and inventor, Nikola Tesla (Figure 2.24). The magnetic field strength at a radial distance from the centre of a current-carrying conductor is calculated using the formula below.

Formula	$B = \frac{\mu_0 I}{2\pi r}$	
Symbol	Variable	SI unit
B	Magnetic field strength	T
I	Charge of particle or object 1	A
r	Radial distance from centre of conductor	m
$\frac{\mu_0}{2\pi}$	Magnetic field constant	T m A^{-1}

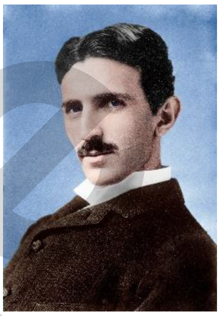


Figure 2.24

The formula features the **magnetic field constant** which has a magnitude of 2.00 x 10^{-7} T m A^{-1} and features the physical constant μ_0 commonly called the **permeability of free space** which is a factor that affects the magnitude and propagation of the magnetic field through free space.

Example 2.22

A straight length of copper wire carries a current of 1.5 A.

Calculate the magnetic field strength 50 cm from the centre of the wire.

$$B = \frac{\mu_0 I}{2\pi r}$$

$$B = 2.00 \times 10^{-7} \frac{1.5}{0.5}$$

$$B = 6 \times 10^{-7}\ \text{T}$$

Example 2.23

A transmission power line carries a current of 500 A.

Calculate the radial distance from the wire at which the magnetic field strength is 22 μT.

$$r = \frac{\mu_0 I}{2\pi B}$$

$$r = 2.00 \times 10^{-7} \frac{500}{22 \times 10^{-6}}$$

$$r = 4.5\ \text{m}$$

Question

The diagram below shows the magnetic field around a straight current-carrying a conductor.

(a) Sketch the magnetic field around the wire using the current vector below.

(2 marks) **KA1**

(b) The wire carries a current of 20 A.

Calculate the radial distance from the wire at which the magnetic field strength is 4 x 10^{-5} T

Give your answer in centimetres.

(3 marks) **KA4**

(c) Calculate the magnetic field strength a radial distance of 25 cm from the centre of the wire.

(2 marks) **KA4**

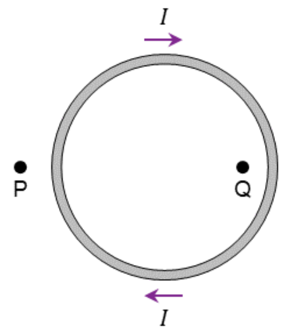
(d) The current through the conductor is increased.

Calculate the current if the magnetic field strength 30 cm from the wire is 2 x 10^{-5} T.

(2 marks) **KA4**

Question

The diagram below shows a loop conductor carrying a current.



(a) Use the right-hand rule to determine the direction of the magnetic field at P and Q.

P: ____________________ Q: ____________________ (2 marks) **KA4**

(b) The current in the loop is tripled.

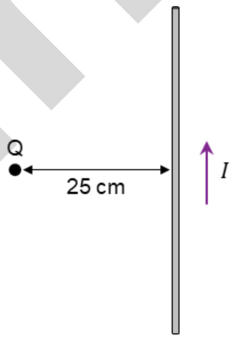
State and explain how the magnetic field at P and Q changes when the current is tripled.

____

____ (2 marks) **KA1**

Question

The diagram below shows a straight vertical wire carrying a 50 A current.



(a) Point Q is 25 cm west of the wire.

State the direction of the magnetic field at Q.

____ (1 mark) **KA2**

(b) Calculate the magnetic field strength at Q.

(2 marks) **KA4**

Magnetic force on a charged particle

A charged particle experiences a magnetic force when it moves in a magnetic field. The magnitude of the magnetic force on a moving charge depends on the velocity and charge of the particle, the magnetic field strength, and the angle between the velocity and magnetic field. The magnetic force on a moving charge in a uniform magnetic field is calculated using the formula below.

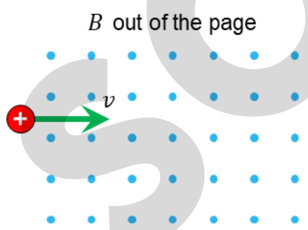
Formula	$F = qvBsin\theta$	
Symbol	**Variable**	**SI unit**
F	Magnetic force	N
q	Charge on particle	C
v	Velocity of particle	$m\ s^{-1}$
B	Magnetic field strength	T
θ	Angle between the field and velocity	(°)

The direction of the magnetic force on a moving charge is determined using the right-hand palm rule. For a positive charge, the direction of the magnetic force is the open push of the palm when the right thumb points in the direction of the velocity and the fingers point in the direction of the magnetic field. For a negative charge, the direction of the magnetic force is obtained using the right-hand palm rule and reversing the outcome, or using the left hand.

Example 2.27

A proton moving at 1 x 10^5 m s^{-1} enters perpendicular to 0.4 T magnetic field.

Calculate the magnitude and determine the direction of the force on the proton.



F	=	$qvBsin\theta$
F	=	$1.6 \times 10^{-19} \times 1 \times 10^{5} \times 0.4 \times sin90$
F	=	6.4×10^{-15} N, vertically downwards

Example 2.28

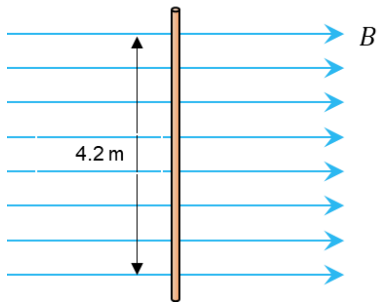
An electron moving at 2 x 10^6 m s^{-1} enters perpendicular to 0.5 T magnetic field.

Calculate the magnitude and determine the direction of the force on the electron.

F	=	$qvBsin\theta$
F	=	$1.6 \times 10^{-19} \times 2 \times 10^{6} \times 0.5 \times sin90$
F	=	1.6×10^{-13} N, vertically upwards

Question

The diagram below shows a straight length of wire inside a 50 mT magnetic field.



(a) The wire experiences a magnetic force of 0.4 N, into the page.

Calculate the magnitude and state the direction of the current in the wire.

(3 marks) **KA4**

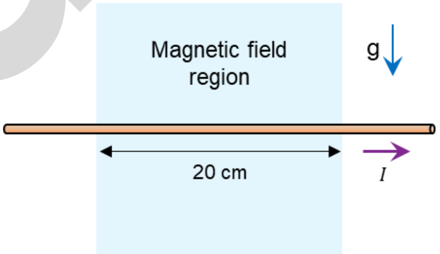
(b) The wire is rotated so that the current is at an angle of 30° to the field.

Use proportionalities to determine the magnetic force on the wire.

(2 marks) **KA4**

Question

The diagram below shows a 5.0 g wire carrying a 2.5 A current in a magnetic field.



(a) State the direction of the magnetic force required to levitate the wire.

(1 mark) **KA1**

(b) Calculate the magnitude of the magnetic field required to levitate the wire.

(3 marks) **KA4**

A charged particle moving at right angles to a uniform magnetic field experiences a force of constant magnitude at right angles to the velocity. The force changes the direction but not the speed of the charged particle and hence the particle moves with uniform circular motion.

- Explain how the velocity dependence of the magnetic force on a charged particle causes the particle to move with uniform circular motion when it enters a uniform magnetic field at right angles.
- Derive $r = \frac{mv}{Bq}$ for the radius r of the circular path of an ion of charge q and mass m that is moving with speed v at right angles to a uniform magnetic field of magnitude B.
- Solve problems involving the use of $r = \frac{mv}{Bq}$

A moving charge experiences a magnetic force at right angles to its velocity when moving perpendicular to a uniform magnetic field. The magnetic force causes the charged particle to move with uniform circular motion inside the field, as shown in Figure 2.26.

Figure 2.26: Uniform circular motion of moving charges inside a uniform magnetic field.

A formula for the radius of the circular path is derived by asserting that the magnetic force causes the centripetal acceleration of a charge moving perpendicular to a uniform magnetic field.

$$\begin{aligned} qvB &= \frac{mv^2}{r} \\ q\cancel{v}B &= \frac{mv^{\cancel{2}}}{r} \\ qB &= \frac{mv}{r} \\ r &= \frac{mv}{qB} \end{aligned}$$

The derived formula is used to calculate the radius of the circular path of a moving charge.

Formula	$r = \frac{mv}{qB}$	
Symbol	**Variable**	**SI unit**
r	Radius of the circular path	m
m	Mass of particle	kg
v	Velocity of particle	m s^{-1}
q	Charge of particle	C
B	Magnetic field strength	T

Period of circular motion

A cyclotron contains two electromagnets positioned above and below the plane of the dees that produce a permanent and uniform magnetic field, as shown in Figure 2.27.

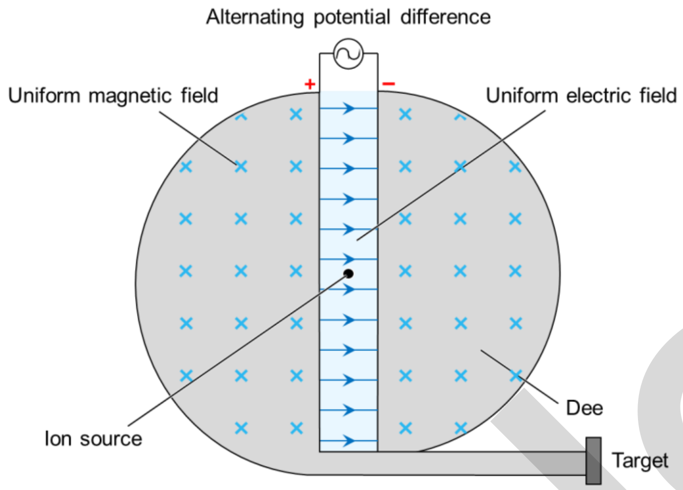


Figure 2.27: Uniform magnetic field through the dees.

The magnetic field exerts a force that effectively steers the ions repeatedly in the direction of the electric field, which does work on the ions and increases their speed. The radius increases with the speed of the ion, but the period of circular motion is constant as the increase in speed is offset by the increase in the length of the circular path. The period is independent of the speed of the ion, as shown in the derived formula below.

$$\frac{qBr}{m} = \frac{2\pi r}{T}$$

$$\frac{qB\cancel{r}}{m} = \frac{2\pi \cancel{r}}{T}$$

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

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

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

Symbol	Variable	SI unit
T	Period of circular motion	s
m	Mass of ion	kg
q	Charge of ion	C
B	Magnetic field strength	T

Example 2.30

A proton is accelerated by a cyclotron with a 0.8 T magnetic field.

Calculate the period of the circular motion of the proton.

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

$$T = \frac{2\pi 1.673 \text{ x } 10^{-27}}{1.6 \text{ x } 10^{-19} \text{ x } 0.8}$$

$$T = 8.2 \text{ x } 10^{-8} \text{ s}$$

Lenz's Law states that the direction of a current created by an induced emf is such that it opposes the change in magnetic flux producing the emf. Hence: $emf = N\frac{\Delta\phi}{\Delta t}$.

- Use the Law of conservation of energy to explain Lenz's Law.
- Use Lenz's Law to determine the direction of the current produced by the induced emf.
- Use Lenz's Law to explain the production of eddy currents.

In 1834, Russian physicist Heinrich Lenz (Figure 2.32) investigated Faraday's Law of induction and discovered that the induced current always flows in a direction that produces a magnetic field opposing the change in magnetic flux. This is known as **Lenz's Law**.

Figure 2.32: Heinrich Friedrich Emil Lenz (1804−1865).

Example 2.35

Figure 2.33 shows a bar magnet and a loop conductor. In image 1, there is no induced current as the magnet is stationary, and there is no change in magnetic flux through the loop. In image 2, the downward magnetic flux through the loop increases as the magnet is moved downwards. Lenz's Law states that the induced current flows anticlockwise and produces an upward-pointing magnetic field to oppose the increase in downward flux. In image 3, the downward flux through the loop decreases as the bar magnet is pulled away from the loop. Lenz's Law states that the induced current flows clockwise and produces a downwards magnetic field to oppose the decrease in downward flux.

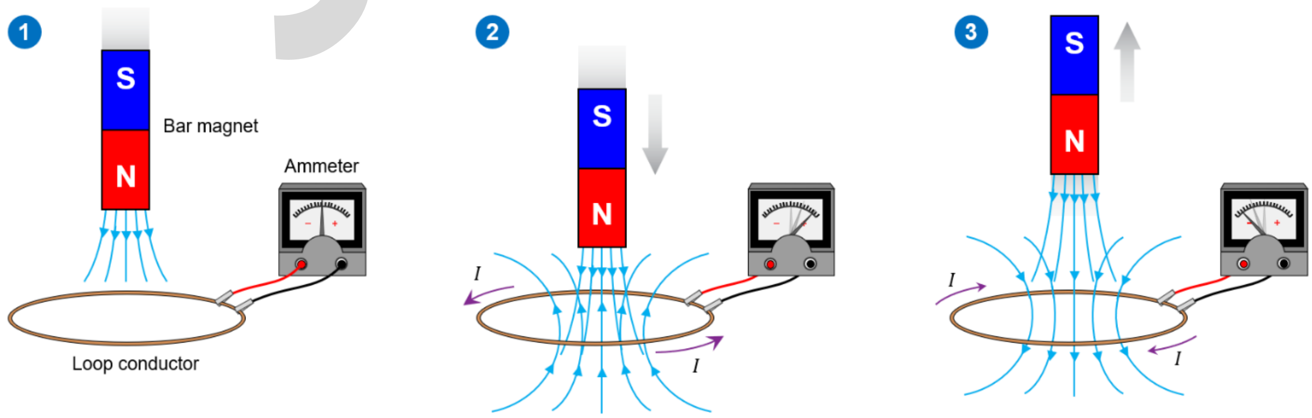


Figure 2.33: Examples of Lenz's Law.

Conservation of energy

The *emf* induced in a conductor by the change in magnetic flux is a source of electrical energy. The Law of conservation of energy states that an energy source cannot be created, so there must be a source of input energy that is transformed into electrical energy in the conductor. Figure 2.34 shows a bar magnet being moved towards a loop conductor by a device or person. A current is induced in the loop which produces a magnetic field. The north pole of the induced magnetic field faces the north pole of the approaching bar magnet producing a repulsive magnetic force. Work is done in overcoming the repulsive magnetic force, and this work is transformed into electrical energy in the loop. In this way, Lenz's Law is consistent with the Law of conservation of energy.

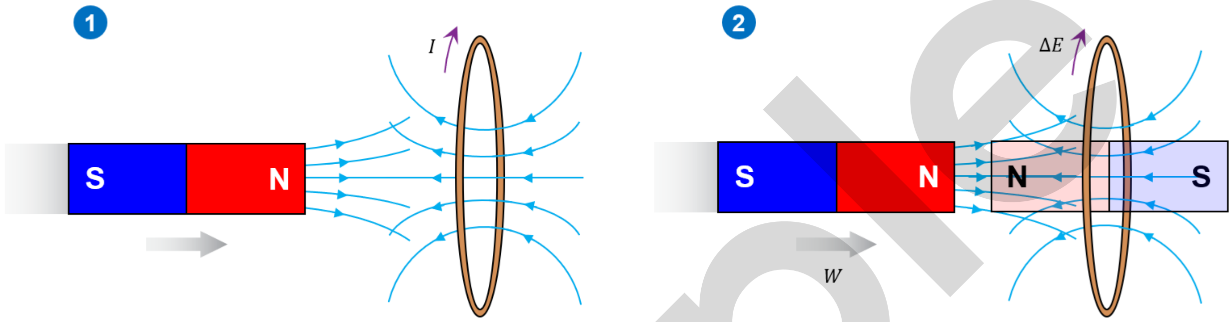


Figure 2.34: Conservation of energy in Lenz's Law.

Eddy currents

Eddy currents are loops of electrical current induced within conductors by a changing magnetic flux. Figure 2.35 shows a sheet of copper between the poles of a strong magnet. As the copper sheet is pulled to the right of page, there is a change in magnetic flux through the areas labelled A and B. The change in magnetic flux through these areas induces circular loops of current called eddy currents. The magnetic field of the strong magnet exerts a magnetic force on the eddy currents, and by the right-hand rule, this force is directed to the left of page, which is opposite to the pulling force. The magnetic force exerted on the eddy currents is called a **braking force** as it acts in the opposite direction to the motion of the copper sheet.

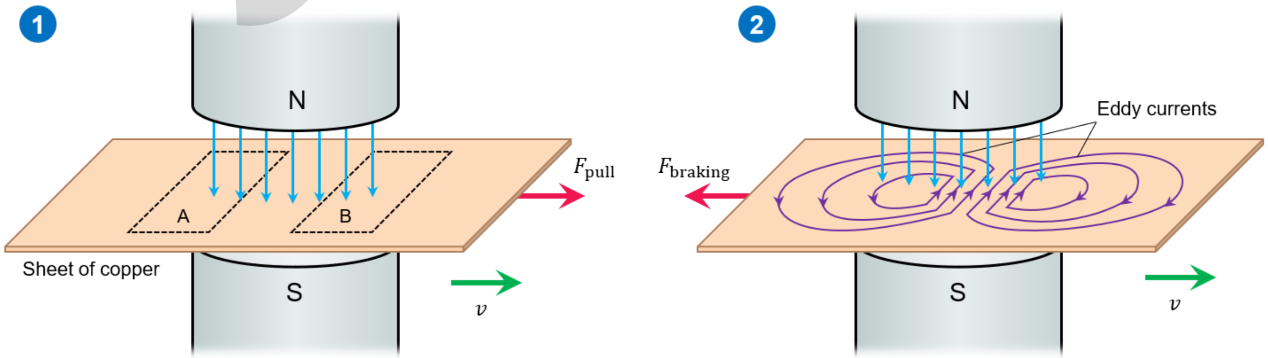


Figure 2.35: Production of eddy currents in a copper sheet.

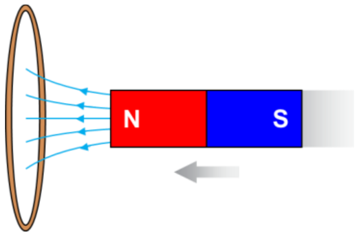
Eddy currents have many practical applications in science and technology.

Question

Lenz's Law states that an induced current flows in a direction that produces a magnetic field opposing the change in magnetic flux.

State whether the induced current flows clockwise or anticlockwise in the loop in the following:

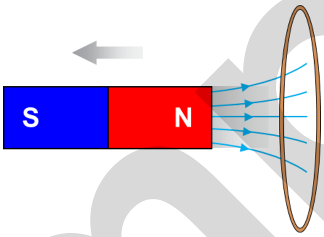
(a) A bar magnet is moved to the left in the direction of the loop.



Direction of induced current.

____ (1 mark) **KA1**

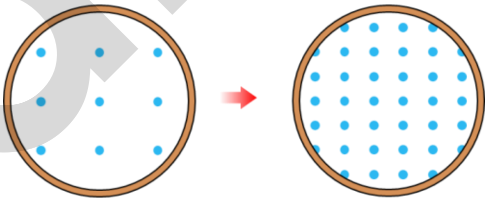
(b) A bar magnet is moved away from the loop.



Direction of induced current.

____ (1 mark) **KA1**

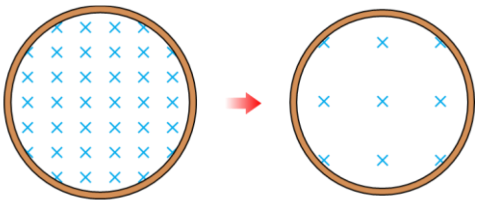
(c) The magnetic flux through a loop is increased



Direction of induced current.

____ (1 mark) **KA1**

(d) The magnetic flux through a loop is decreased.



Direction of induced current.

____ (1 mark) **KA1**

Transformers allow generated voltage to be either increased or decreased before it is used.

A transformer consists of a primary coil (with N_p turns) with a potential difference (V_p) and a secondary coil (with N_s turns) with a potential difference (V_s).

The relationship between the potential differences is given by the formula: $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

- Describe the purpose of transformers in electrical circuits.
- Compare step-up and step-down transformers.
- Solve problems involving the use of $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

A **transformer** is a device that changes or transforms an alternating voltage before it is used by a consumer. Transformers consist of two coils of wire called the **primary** and **secondary coils** linked by an insulating material or a laminated iron core (Figure 2.40). Alternating current flows through the primary coil producing a changing magnetic field. The changing magnetic field produced by the primary coil passes through the iron core and induces an alternating emf in the secondary coil.

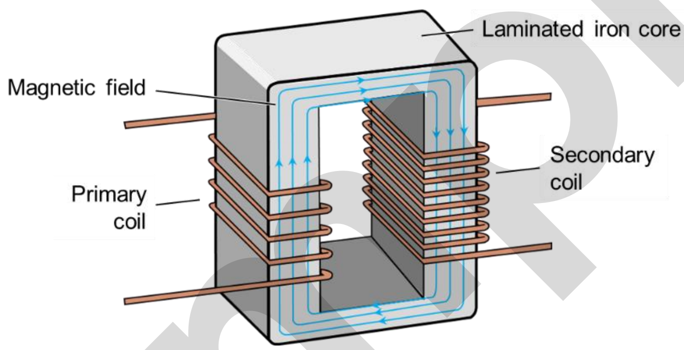


Figure 2.40: Components of a transformer.

Transformers have energy losses associated with electrical resistance in the coils and with the production of eddy currents in the core. The iron core is a conductor, so eddy currents are produced by the change in magnetic flux around the primary coil. The eddy currents circulate the core, setting up unwanted opposing flux and wasting energy as heat due to the resistance of the core material. Eddy currents in a transformer are minimised by laminating the core. The laminated material increases electrical resistance which confines the eddy currents to smaller areas with smaller emf's.

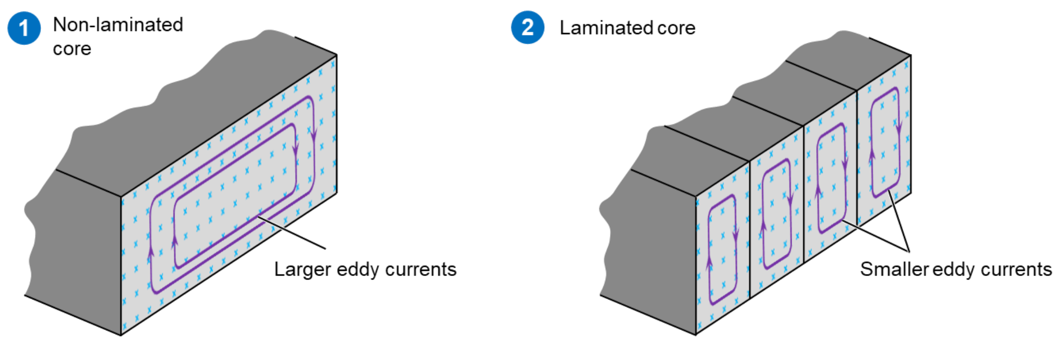
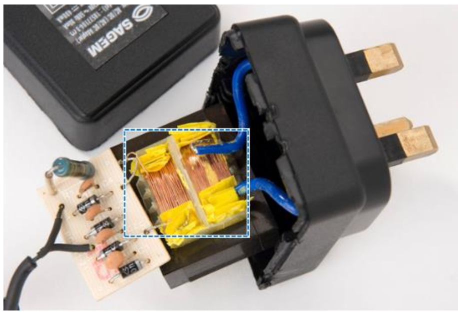


Figure 2.41: Eddy currents in a non-laminated core (left) and a laminated core (right).

Question

The diagram below shows transformers in a microwave oven and a mobile phone adapter.



(a) The microwave oven contains a step-up transformer, and the mobile phone adapter contains a step-down transformer.

(1) State two differences between step-up and step-down transformers.

____

____ (2 marks) **KA1**

(2) State one similarity in the functions of step-up and step-down transformers.

____

____ (1 mark) **KA1**

(b) The microwave transformer contains a primary coil with 150 turns and secondary coil with 1500 turns that are each wrapped around a laminated iron core.

(1) Calculate the voltage in the secondary coil if the voltage in the primary coil is 240 V.

(2 marks) **KA4**

(2) State the advantage of laminating the iron core.

____

____ (1 mark) **KA2**

(c) The mobile phone adapter transforms 240 V to 5 V.

Calculate the number of turns in the primary coil if there are 15 turns in the secondary coil.

(2 marks) **KA4**

Electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.

The speed of a wave, its frequency, and its wavelength are related through the formula $v = f\lambda$.

- Relate the orientation of the receiving antenna to the plane of polarisation of radio or television waves.
- Solve problems using $v = f\lambda$.

Electromagnetic waves are composed of oscillating electric and magnetic fields. The electric and magnetic fields are **mutually perpendicular** meaning that the two field types are 90 degrees to one another at any position on the wave. Electromagnetic waves are transverse as the electric and magnetic fields oscillate in a direction perpendicular to the wave propagation (Figure 3.11).

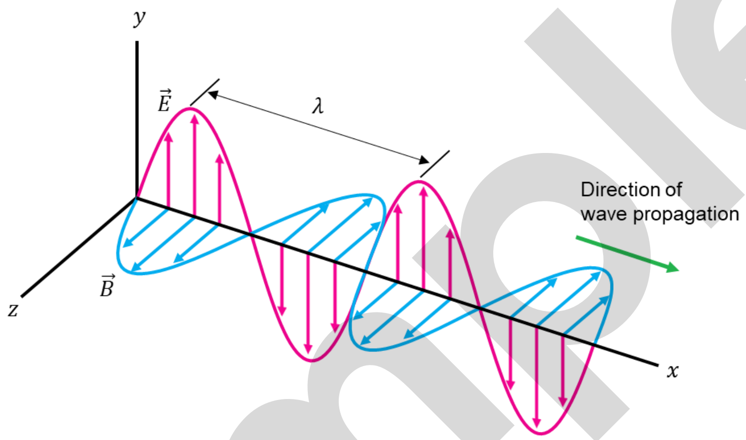


Figure 3.11: Electromagnetic wave.

The electric field vectors of an electromagnetic wave oscillate in a plane perpendicular to the wave propagation. The plane containing the electric field vectors is called the **plane of polarisation**. An electromagnetic wave is described as plane-polarised when the oscillation of the electric field is restricted to a single plane. Figure 3.12 shows an electromagnetic wave that is vertically plane-polarised as the electric field oscillates along the y-axis.

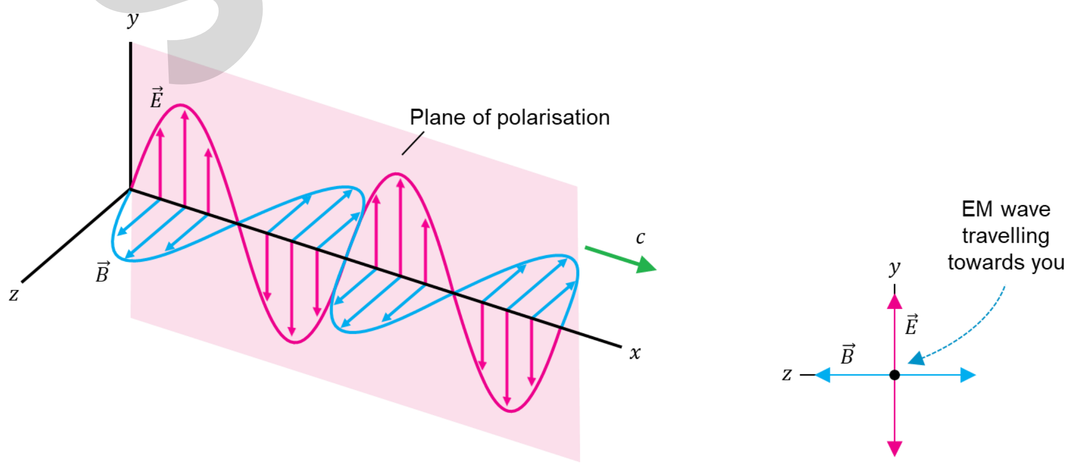


Figure 3.12: Vertically plane-polarised electromagnetic wave.

When two or more electromagnetic waves overlap, the resultant electric and magnetic fields at a point can be determined using the principle of superposition.

When the waves at a point are in phase, 'constructive interference' occurs.

When the waves at a point are out of phase, 'destructive interference' occurs.

- Use the principle of superposition to describe and represent constructive and destructive interference.

Electromagnetic waves are transverse waves composed of oscillating electric and magnetic fields. When two or more electromagnetic waves of the same frequency overlap, the electric and magnetic fields add together vectorially, and the resultant fields at a point are determined using the **principle of superposition**. When two overlapping waves are in phase at a point, **constructive interference** occurs, and the resultant electric and magnetic fields increase in magnitude (Figure 3.20). Conversely, when two overlapping waves are out of phase at a point, **destructive interference** occurs, and the resultant electric and magnetic fields decrease in magnitude. When two overlapping waves with equal frequencies are out of phase by half a wavelength $\left(\frac{1}{2}\lambda\right)$, the resultant electric and magnetic fields are zero, and complete cancellation occurs (Figure 3.20).

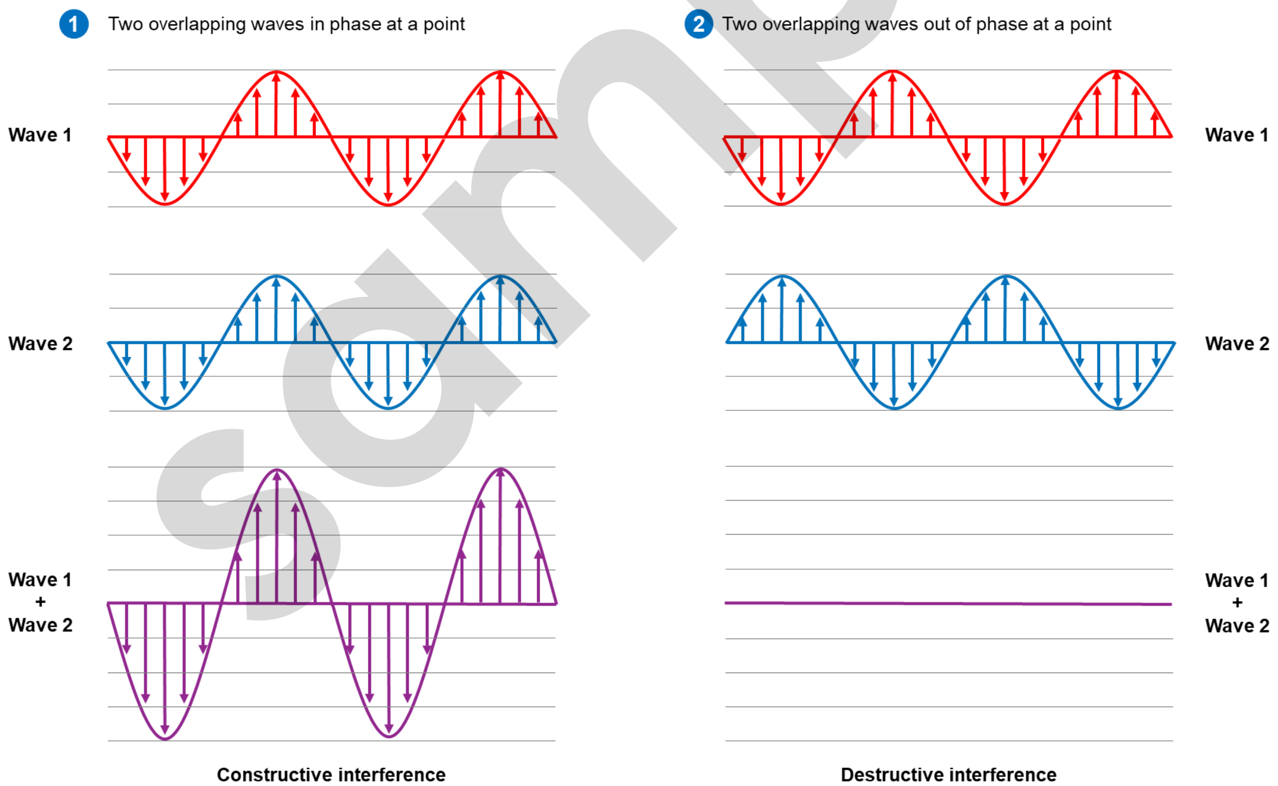


Figure 3.20: Constructive and destructive interference of electromagnetic waves.

In the context of visible light, constructive interference of electromagnetic waves increases light intensity at the point of overlap, and destructive interference reduces light intensity at the point of overlap. Complete cancellation results in darkness being observed at the point of overlap.

Example 3.04

Figure 3.22 shows two monochromatic wave sources, S_1 and S_2, positioned along the y-axis at points equidistant from the origin. P_0 is a point on the x-axis and is equidistant from S_1 and S_2. Waves that leave S_1 and S_2 in phase arrive at P_0 in phase and interfere constructively as they travel the same distance to P_0 at the same time. Similarly, waves leaving S_1 and S_2 in phase arrive in phase at P_1 and interfere constructively as the path length from S_2 to point P_1 is exactly one wavelength greater than the path length from S_1 to P_1. The two waves have a **path difference** of one wavelength (1λ) resulting in a wave crest from S_1 arriving at P_1 exactly one cycle earlier than a crest emitted at the same time from S_2. At point P_2, the path difference is two wavelengths (2λ), and the two waves arrive in phase at P_2, resulting in constructive interference. Constructive interference of two waves occurs when the path difference from the two sources is an integral number of wavelengths ($m\lambda$). Destructive interference occurs when the path difference for the two sources is a half-integral number of wavelengths $\left(m+\frac{1}{2}\right)\lambda$ and two waves arrive at a point a half-cycle out of phase such as at point P_3.

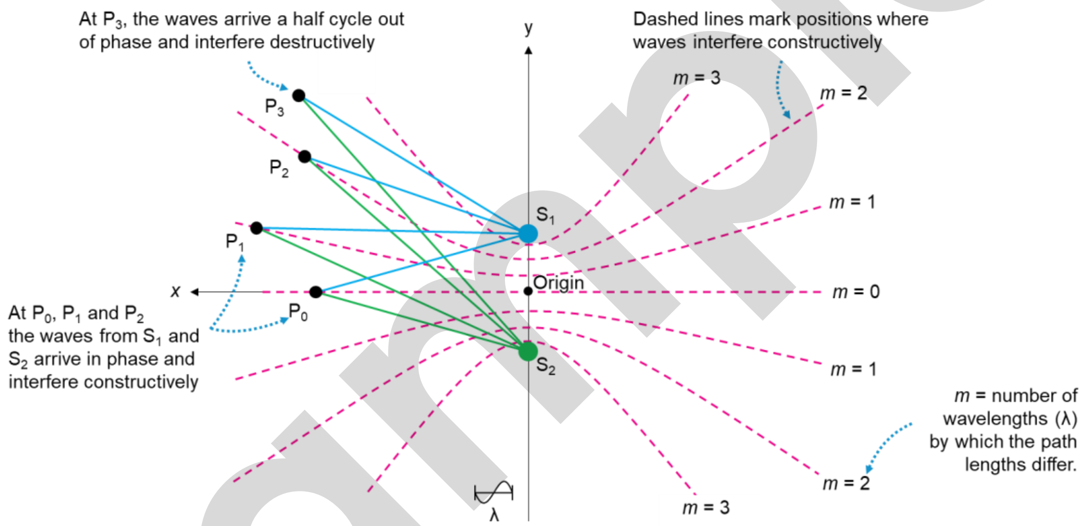


Figure 3.22: Interference of waves from two monochromatic wave sources.

The conditions for constructive and destructive interference are summarised in Figure 3.23.

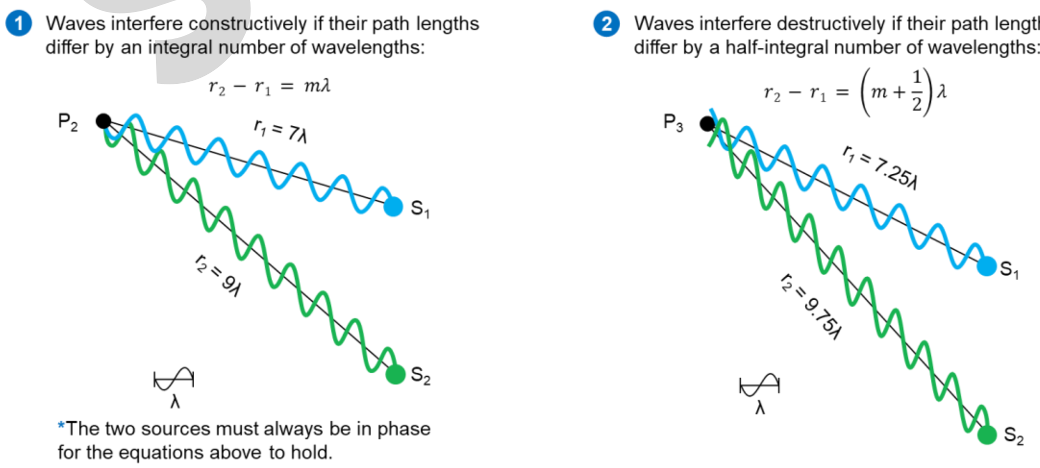


Figure 3.23: Conditions for the constructive and destructive interference of waves.

Young's double-slit experiment

Young demonstrated the wave nature of light by producing an **interference pattern** using two light sources. Young knew there was no practical way to demonstrate the interference of light waves using two monochromatic or two incandescent light sources as the emitted waves do not maintain a constant phase relationship. To solve the problem, Young produced coherent light by passing light from a single monochromatic source through a single slit and then splitting the light using a pair of slits that were equidistant from the single slit (Figure 3.25). In this way, any random phase change in the light source affects the pair of slits equally and does not change their relative phase.

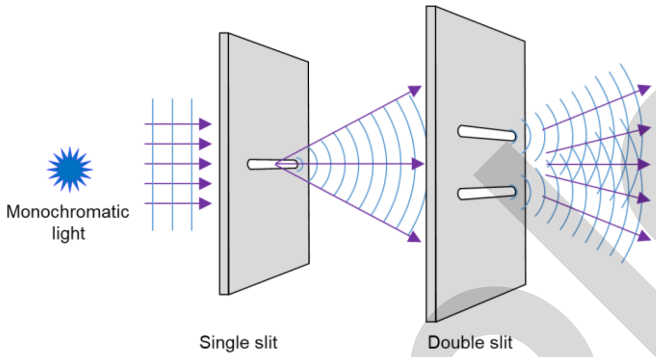


Figure 3.25: Young's apparatus for producing coherent wave sources.

Figure 3.26 shows the experimental apparatus used by Thomas Young. Monochromatic light passes through a narrow slit, S_0, approximately 1 μm wide and falls on a screen with two other narrow slits, S_1 and S_2, each approximately 1 μm wide and a few micrometres apart. The wavefronts spread out from slit S_0 and reach slits S_1 and S_2 in phase because they travel equal distances from S_0. Therefore, the waves emerging from slits S_1 and S_2 are in phase, and S_1 and S_2 are coherent wave sources. The waves diffracting outwards from S_1 and S_2 interfere with one another and produce an interference pattern on a screen placed at a distance from the slits.

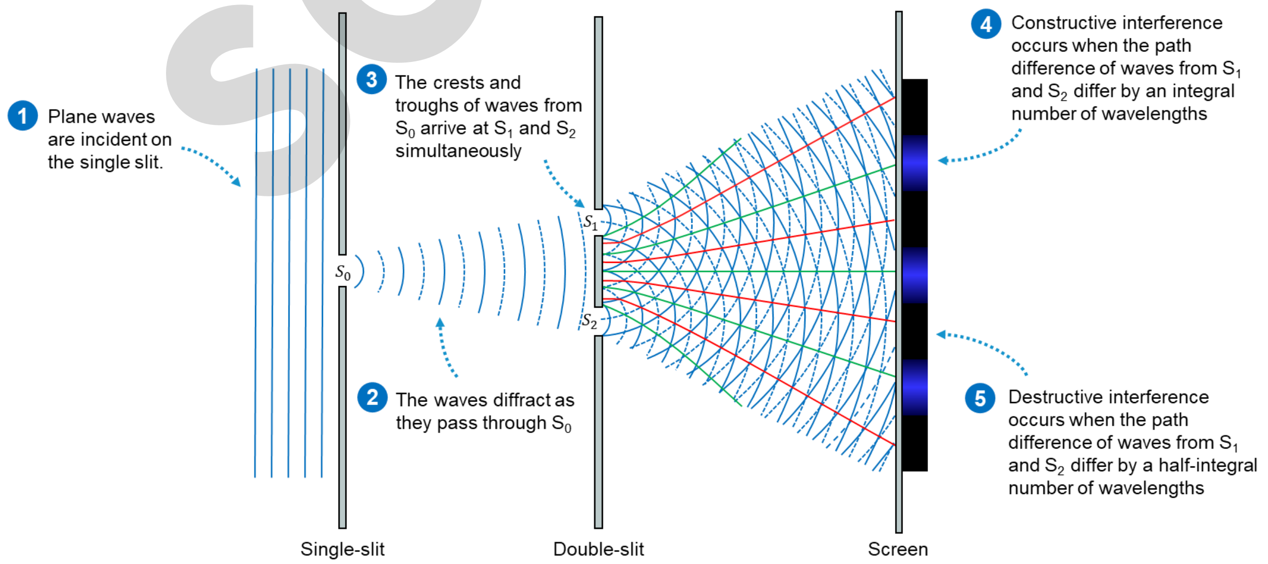


Figure 3.26: Young's double-slit experiment

Two-slit interference pattern

An interference pattern is a succession of bright and dark bands, called **fringes**, produced by the interference of waves from the double-slit (Figure 3.27). The bright fringes, called **orders of maxima**, are regions where the path difference is an integral number of wavelengths and the waves interfere constructively. Conversely, the dark fringes, called **orders of minima**, are regions where the path difference is a half-integral number of wavelengths and waves interfere destructively.

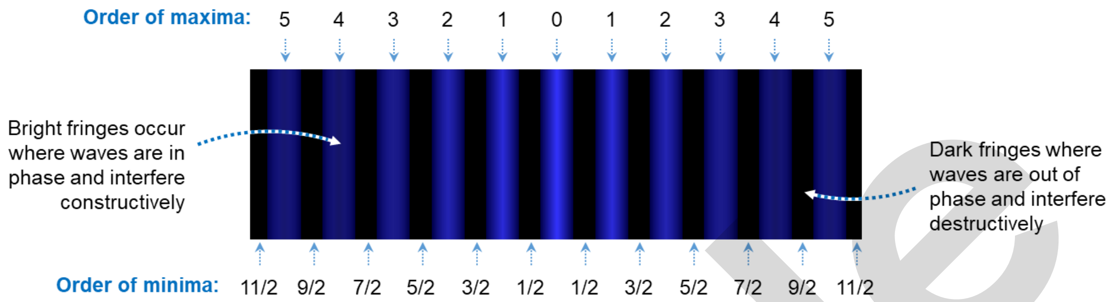


Figure 3.27: Interference pattern produced in a double-slit experiment.

Intensity distribution for two-slit interference

Figure 3.28 shows how light intensity varies with position along the screen for a two-slit interference pattern. The intensity is at a maximum where the fringe number is an integral and decreases to zero where the fringe number is a half-integral. The intensity of maxima decreases either side of the central (zero-order) maxima as light intensity decreases with distance from the source, and the light intensity from each slit by itself is not uniform. Light passing through each slit in the double-slit produces a single-slit diffraction pattern which modulates the two-slit interference pattern resulting in the observed decrease in intensity either side of the central maximum.

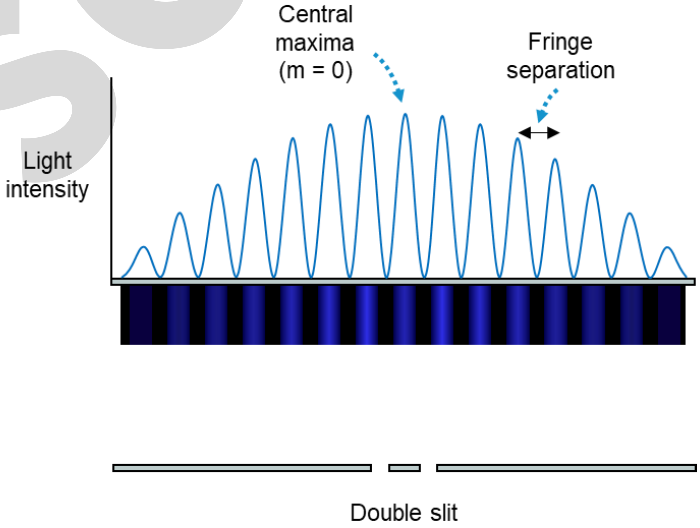


Figure 3.28: Interference pattern produced in a double-slit experiment.

Path difference formula

Figure 3.29 is used to derive a formula to analyse a two-slit interference pattern produced by monochromatic light. The two slits, S_1 and S_2, of the double-slit are separated by a distance, d, and the interference pattern is viewed on a screen that is a distance, L from the double-slit. The distance L is much greater than the distance between the slits d. The lines r_1 and r_2 are **optical paths** that define the path taken by waves of light travelling from S_1 to P_1 and from S_2 to P_1. There is an **optical path difference**, Δr as a wave travelling from S_2 to P_1 travels a greater distance than a wave travelling from S_1 to P_1. Since L is much greater than d, the angle θ_3 is almost zero and the optical paths r_1 and r_2 are almost parallel. Hence, the angles θ_1 and θ_2 are almost 90°, and the triangle S_1S_2Q is right-angled to a good approximation. Furthermore, since the line S_1Q is normal to the line RP_1 and the line S_1S_2 is normal to RP_0, the angles θ and θ_4 are equal. Hence, the optical path difference is calculated as $d\sin\theta$. For a bright fringe to be observed at position P_1 on the screen, the optical path difference must be an integral number of wavelengths ($d\sin\theta = m\lambda$), and for a dark fringe at P_1, the optical path difference is a half-integral number of wavelengths $\left(d\sin\theta = \left(m + \frac{1}{2}\right)\lambda\right)$.

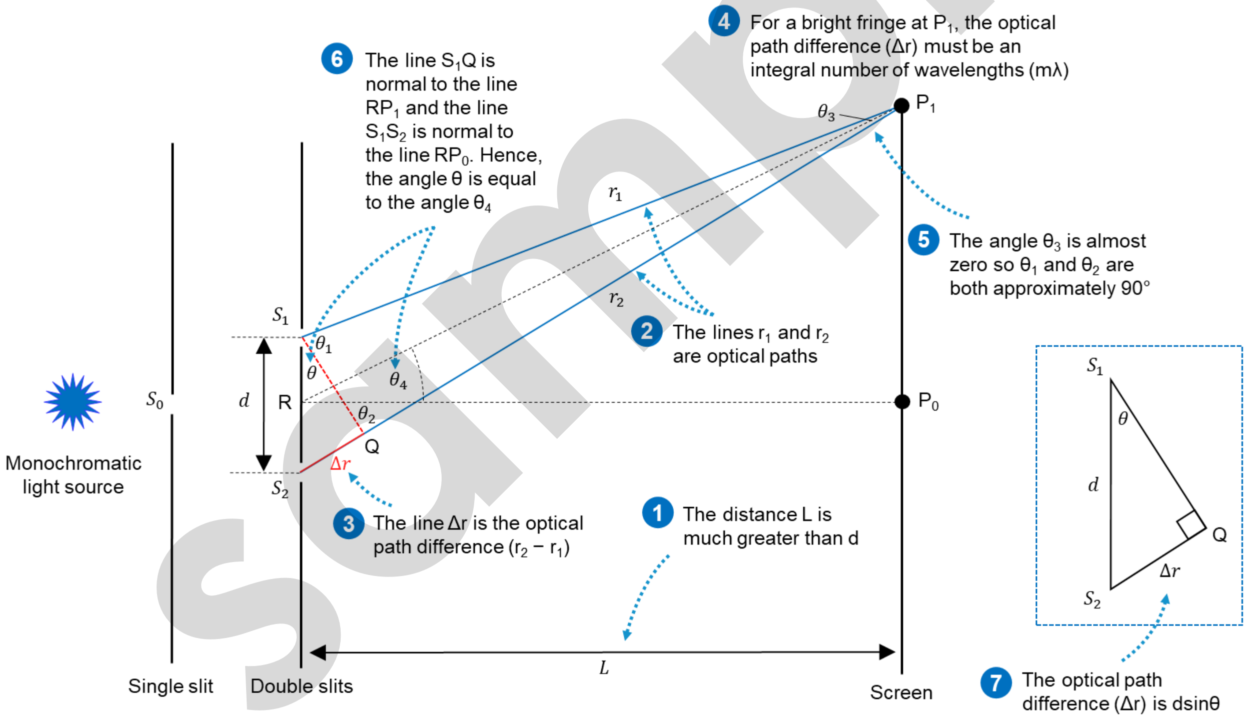


Figure 3.29: Deriving the formula for the optical path difference.

Formula	$d\sin\theta = m\lambda$

Symbol	Variable	SI unit
d	Distance between the two slits	m
θ	The angular position of the maxima or minima	°
m	Order or maxima or minima	
λ	Wavelength	m

Fringe separation formula

Figure 3.30 is used to derive a formula to calculate the fringe separation of maxima and minima in a two-slit interference pattern produced by monochromatic light. The diagram shows the distance between slits, d, the distance between the double-slit and screen, L and the fringe separation, Δy.

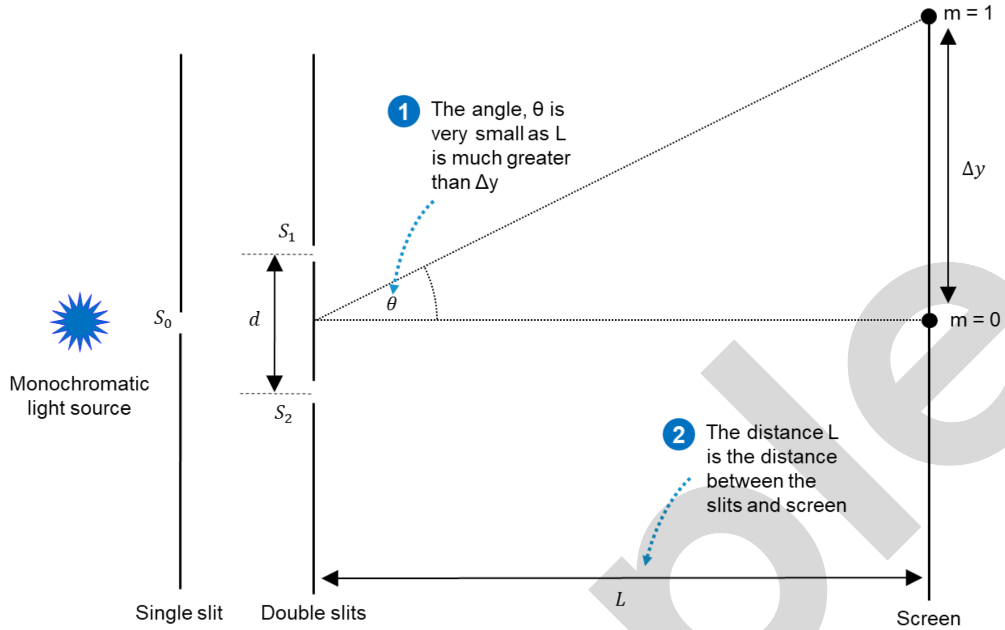


Figure 3.30: Deriving the formula used to calculate the fringe separation.

The fringe separation can be calculated using trigonometry:

$$\tan\theta = \frac{\Delta y}{L}$$

Since Δy is much smaller than L, the angle θ is small, and $\sin\theta$ is approximately equal to $\tan\theta$, hence:

$$\sin\theta = \frac{\Delta y}{L}$$

$$\frac{m\lambda}{d} = \frac{\Delta y}{L}$$

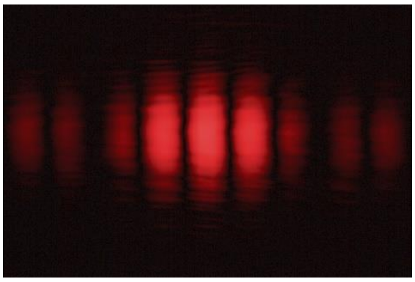
The fringe separation is constant between all adjacent orders of maxima and minima (m), hence:

Formula	$\Delta y = \frac{\lambda L}{d}$

Symbol	Variable	SI unit
Δy	Fringe separation	m
λ	Wavelength	m
L	Distance between double-slit and screen	m
d	Distance between the two slits	m

Question

The photograph below was produced by illuminating two slits separated by 75 µm with laser light.



The wavelength of the laser light was 632.8 nm.

(a) Calculate the angle between the central and second order maxima.

(2 marks) **KA4**

(b) Determine the order of maxima observed at an angle of 2.42° from the central maxima.

(2 marks) **KA4**

(c) The two slits are 0.6 m from the screen.

Calculate the fringe separation.

(2 marks) **KA4**

(d) State the effect of the following changes on the fringe separation:

(1) The distance between the slits and screen is halved.

________________________________ (1 mark) **KA1**

(2) The distance between slits is doubled.

________________________________ (1 mark) **KA1**

(e) The laser is a coherent wave source.

(1) State one property of a coherent wave source.

________________________________ (1 mark) **KA1**

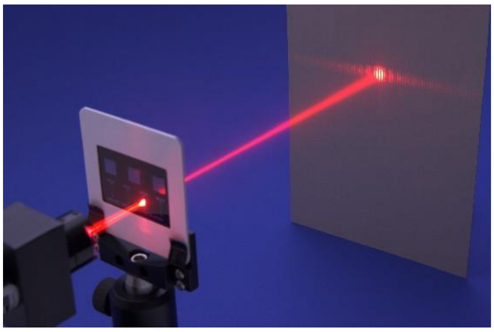
(2) State two properties of laser light.

____

________________________________ (2 marks) **KA1**

Question

The photograph below shows a two-slit interference pattern produced with a red laser (λ = 650 nm).



The screen is 0.50 m from two slits separated by 0.40 mm.

(a) Calculate the fringe separation.

(2 marks) **KA4**

(b) Show that the angular separation between two adjacent maxima is constant.

(3 marks) **KA4**

(c) Explain why a bright fringe is observed at the position of the central order maxima.

____

____

____

____ (2 marks) **KA1**

(d) The laser is replaced, and the fringe separation with the new laser is 0.52 mm.

Calculate the wavelength of the new laser.

(2 marks) **KA4**

(e) State why laser light does not have to be passed through a single slit before the two slits.

____ (1 mark) **KA1**

Diffraction grating formula

Figure 3.34 shows a diffraction grating in which N slits are equally spaced a distance d apart. This is a top-down view of the grating, and the slits extend above and below the page. Only ten slits are shown, but most practical gratings have hundreds or even thousands of slits. Parallel light waves of wavelength, λ approach from the left of page and are transmitted through the slits. The crest of a light wave arrives simultaneously at each of the slits, causing the wave emerging from each slit to be in phase with the wave emerging from every other slit. The emerging waves spread out, and after a short distance, they all overlap and interfere with each other.

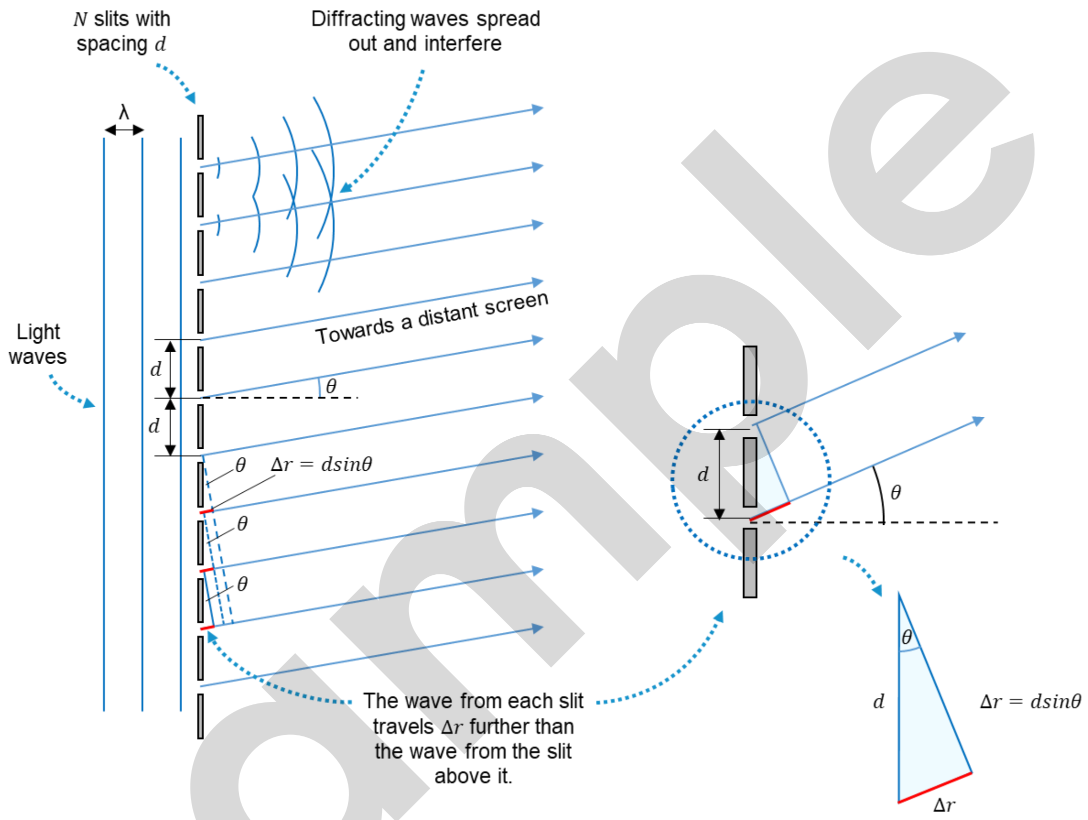


Figure 3.34: Diffraction of light waves through a transmission grating.

The diffracting waves produce an interference pattern on a screen positioned behind the grating. The light wave at the screen is the superposition of N waves, from N slits, as they diffract and overlap. The optical paths from neighbouring slits are approximately parallel as, again, the distance to the screen is very large in comparison with the slit spacing. Figure 3.34 shows the wave from one slit travels distance $\Delta r = d\sin\theta$ further than the wave from the slit above it and $\Delta r = d\sin\theta$ less than the wave below it. If the angle θ is such that $\Delta r = d\sin\theta = m\lambda$, where m is an integer, then the light wave arriving at the screen from one slit will travel exactly m wavelengths more or less than light from the two slits next to it, so these waves are exactly in phase with each other. Furthermore, each of those waves is in phase with waves from the slits next to them, and so on. In other words, N light waves from N different slits will all be in phase with each other when they arrive at a point on the screen at an angle θ such that $d\sin\theta = \mathrm{m}\lambda$.

Example 3.09

Figure 3.35 shows green laser light transmitted through a diffraction grating with five slits. Two sets of optical paths from each of the five slits are shown. In one set of optical paths, the path difference between the waves is one wavelength, and in the other set, the path difference is two wavelengths. In both examples, the waves interfere constructively, and a bright fringe is produced at the position on the screen where the waves overlap.

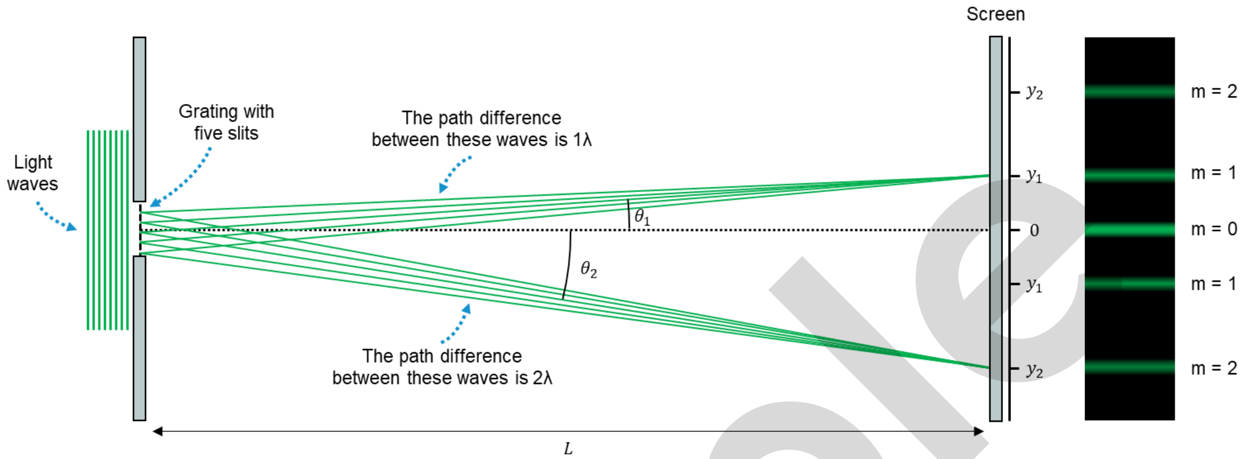
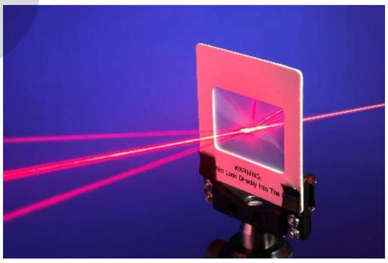


Figure 3.35: Diffraction of green light waves through a transmission grating with five slits.

The grating formula used when analysing the interference pattern produced by a transmission diffraction grating is similar to the one used when analysing a two-slit interference pattern. The minor difference is that the distance between slits in a diffraction grating is commonly stated as the number of lines per millimetre (N) which is the inverse of the slit separation in millimetres $\left(d = \frac{1}{N}\right)$.

Example 3.10

Monochromatic red light illuminates a transmission grating ruled with 500 lines per mm*.



Calculate the distance between slits in the grating.

$$d = \frac{1}{N}$$

$$d = \frac{1}{500 \text{ x } 10^3}$$

$$d = 2 \text{ x } 10^{-6} \text{ m}$$

*A grating with 500 lines in one millimetre has 500,000 (500 x 10^3) lines in one metre.

Diffraction grating pattern

Figure 3.36 shows the diffraction pattern and intensity distribution produced when monochromatic blue light (λ = 450 nm) illuminates a transmission diffraction grating ruled with 600 lines per mm.

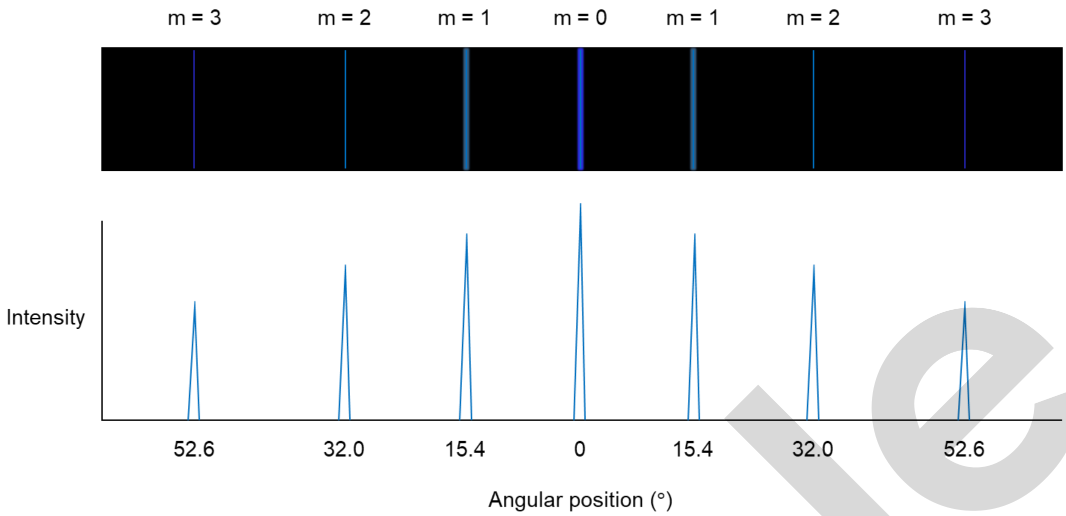


Figure 3.36: Diffraction pattern for monochromatic light (λ = 450 nm).

The pattern shows that there is a central bright fringe with unevenly spaced bright fringes at positions on the screen where the optical path difference is an integral number of wavelengths and the overlapping waves interfere constructively. The intensity of the bright fringes decreases either side of the central maxima. Between the bright fringes are regions of negligible intensity where the overlapping waves are out of phase and interfere destructively. The orders of minima have almost zero intensity because the grating has many closely spaced slits. Even when the optical path difference between adjacent rays of light is as small as one-hundredth of a wavelength, a wave from the tenth slit is half a wavelength out of phase with a wave from the sixtieth slit, and a wave from the eleventh slit is half a wavelength out of phase with a wave from the sixty-first slit. The large number of phase differences between waves ensures that the intensity between maxima is almost zero.

Figure 3.37 shows the relationship between the number of slits and the intensity of bright fringes. The diagram shows that the fringes become narrower and brighter as the number of slits increases.

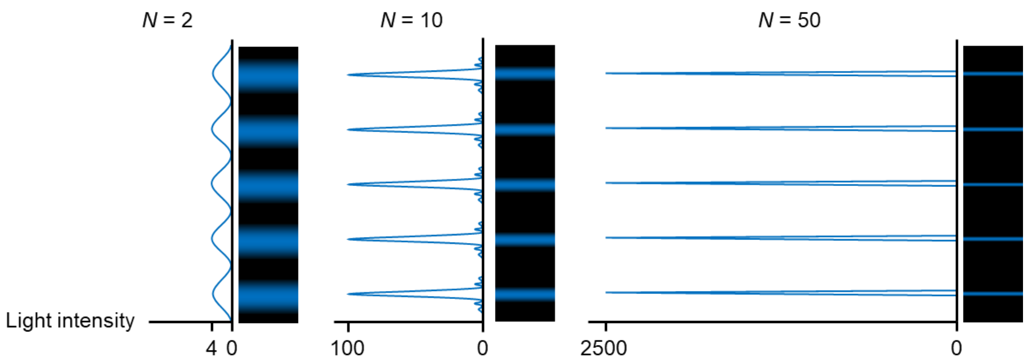


Figure 3.37: Effect of slit number on the width and intensity of bright fringes.

Photon momentum

Following Hertz's discovery of radio waves in 1886, physicists began to study the interaction between electromagnetic radiation and matter. The study of the transmission and reception of radio waves led to the hypothesis that electromagnetic radiation caused electrons to vibrate at the same frequency as the incident electromagnetic waves. The vibrating electrons then respond by emitting electromagnetic waves of the same frequency as depicted in Figure 3.47.

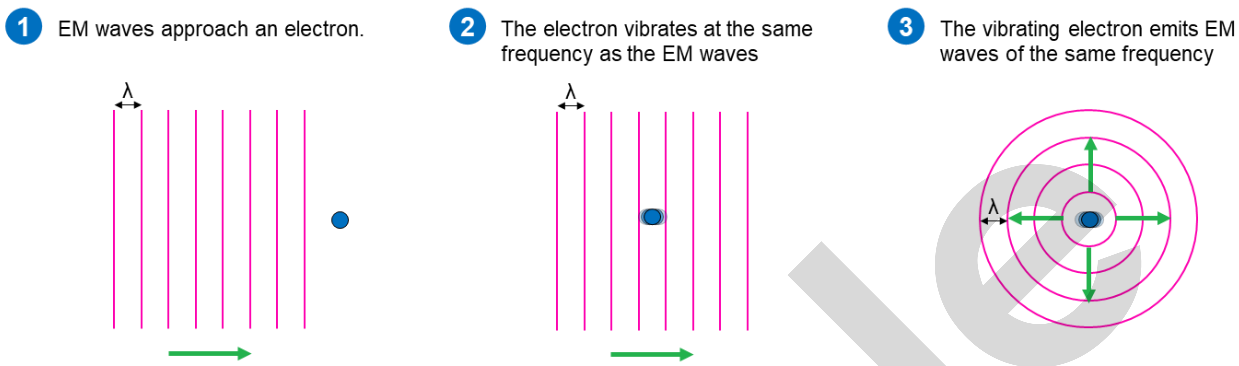
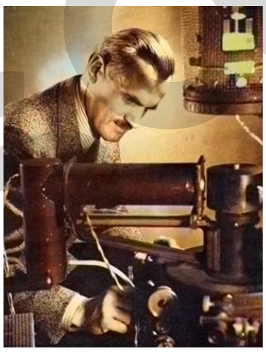


Figure 3.47: Classical prediction of the interaction between EM radiation and matter.

In 1923, American physicist Arthur Compton performed an experiment that contradicted the classical prediction of the interaction between light and matter. Compton fired X-rays at graphite, which is composed of carbon atoms surrounded by free-moving electrons, and observed electrons being scattered by collisions with the incident X-rays as illustrated in Figure 3.48. Compton measured the wavelength of the scattered X-rays and noted it was longer than the wavelength of the incident X-rays which led him to conclude that X-rays behaved as particles (photons) by transferring energy and momentum to electrons in a collision. This phenomenon is called **Compton scattering**.



Arthur Compton (1892-1962)

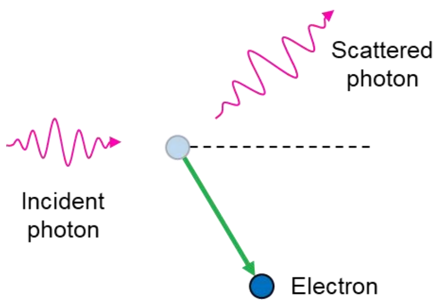


Figure 3.48: Arthur Compton (left) and Compton scattering (right)

Compton published his observations in a paper written later that year. Compton explained the increase in wavelength of the scattered photon by stating that X-rays behaved as particles that transferred energy and momentum during collisions with electrons. Compton then derived a formula to calculate the momentum of a photon.

When light of sufficiently high frequency is incident on matter, it may be absorbed by the matter, from which electrons are then emitted. This is called the 'photoelectric effect'.

The intensity of the incident light affects the number, but not the energy, of emitted electrons.

The minimum frequency, f_0 at which electrons are emitted varies with the type of material and is called the 'threshold frequency'.

The work function, W, of a surface is the minimum energy required to remove an electron from it.

The work function is related to the threshold frequency by $W = hf_0$.

- Describe an experimental method for investigating the relationship between the maximum kinetic energy of the emitted electrons, calculated from the measured stopping voltage using $E_{K_{\max}} = eV_s$ and the frequency of the light incident on a metal surface.
- Describe how Einstein used the concept of photons and the conservation of energy to explain the experimental observations of the photoelectric effect.
- Deduce the formula $E_{K_{\max}} = hf - W$ where $E_{K_{\max}}$ is the maximum kinetic energy of the emitted electrons.
- Plot experimental values of maximum kinetic energy vs frequency, and relate the slope and axes intercepts to the formula: $E_{K_{\max}} = hf - W$
- Solve problems that require the use of $E_{K_{\max}} = hf - W$

In 1887, Heindrich Hertz was investigating the transmission and reception of radio waves with his assistant **Wilhelm Hallwachs** when the two scientists made a profound discovery. Hertz and Hallwachs noted that the sparks produced by electrons passing between the two electrodes in the transmitter became more intense and frequent when exposed to high-frequency visible light or ultraviolet radiation. Hallwachs investigated the phenomenon and concluded that electromagnetic radiation of a sufficient frequency causes the emission of electrons from the surface of a material. The phenomenon became known as the **photoelectric effect**, and its properties were investigated between 1887 and 1900 by **Philipp Lenard** using a device called a photocell shown in Figure 3.51.

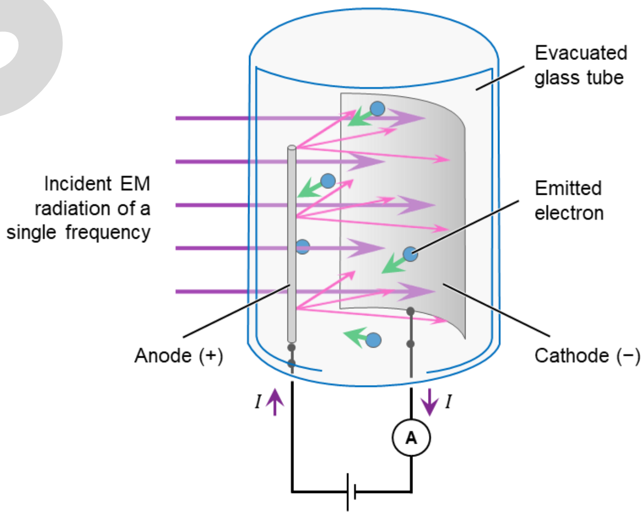


Figure 3.51: Photocell used by Lenard to study the photoelectric effect.

Question

A lithium cathode is illuminated with high-frequency monochromatic light.

Electrons are emitted with a range of kinetic energies.

(a) Explain the range of kinetic energies of the electrons when monochromatic light is used.

(3 marks) **KA1**

(b) State and explain the effect on the emitted electrons when:

(1) The frequency of the electromagnetic radiation is increased.

(2 marks) **KA2**

(2) The intensity of the electromagnetic radiation is decreased.

(2 marks) **KA2**

Question

The data below was obtained for a photoelectric effect experiment using magnesium metal.

f (x 10^{14} Hz)	$E_{K_{max}}$ (x 10^{-19} J)
6.88	0.788
7.41	1.125
8.22	1.644
10.91	3.366
12.00	4.064

(a) Calculate the stopping voltage when the frequency was 7.41 x 10^{14} Hz.

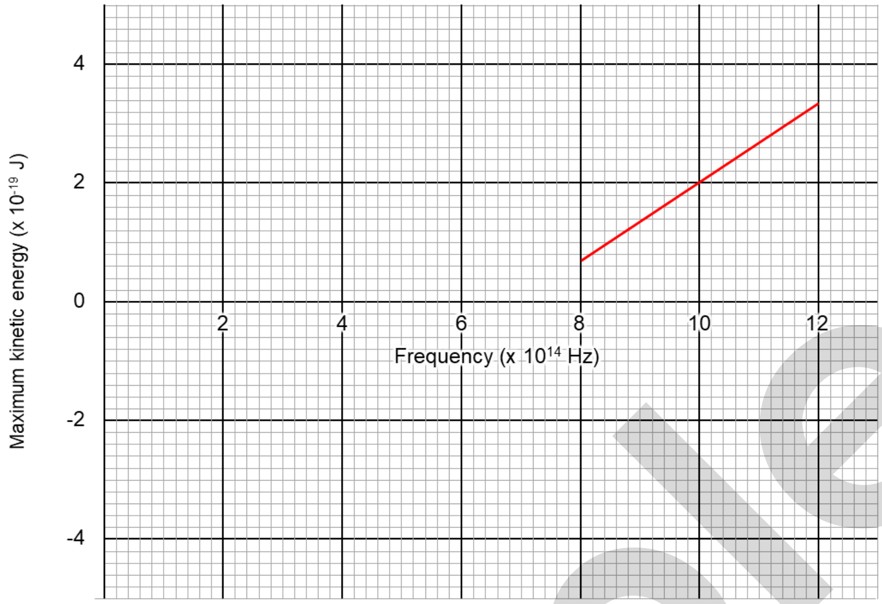
(2 marks) **KA4**

(b) Use the data in the table to determine Planck's constant.

(2 marks) **KA4**

Question

The graph shows the effect of increasing the frequency of incident electromagnetic radiation on the maximum kinetic energy of electrons emitted from the surface of calcium metal.



(a) Use the line of best fit on the graph to determine the following:

(1) The threshold frequency of calcium.

(2 marks) **KA2**

(2) The work function of calcium in eV.

(2 marks) **KA4**

(3) Planck's constant.

(2 marks) **KA4**

(b) Calculate the stopping voltage when the frequency is 10 x 10^{14} Hz.

(2 marks) **KA4**

(c) The calcium metal is oxidised over time which increases its work function.

On the axes above, draw a line showing the results you would expect to obtain from repeating the experiment using oxidised calcium.

(1 mark) **KA2**

X-ray photons can be produced when electrons that have been accelerated to high speed interact with a target. This is done in a simple X-ray tube.

The three main features of the spectrum of the X-rays produced in this way are:

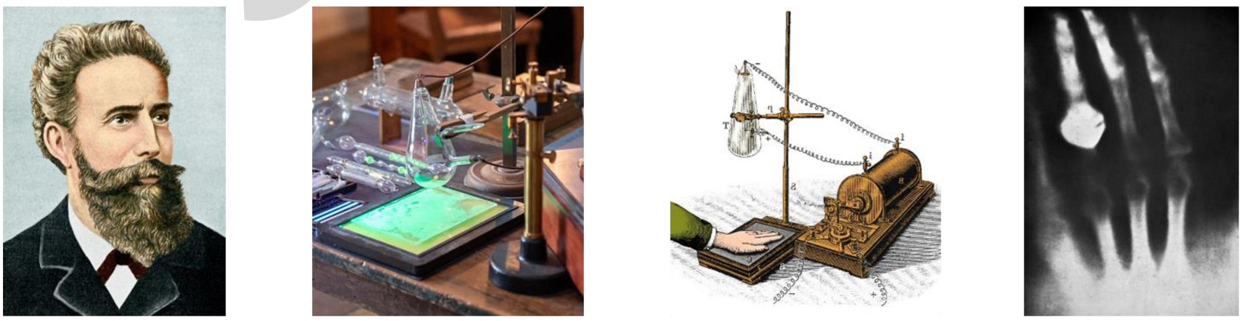
— a continuous range of frequencies (bremsstrahlung)

— a maximum frequency given by $f_{\max} = \frac{e\Delta V}{h}$ where ΔV is the potential difference across the X-ray tube

— high-intensity peaks at particular frequencies (known as characteristic X rays).

- Describe the purpose of the following features of a simple X-ray tube: filament, target, high-voltage supply, evacuated tube, and a means of cooling the target.
- Sketch a graph of the spectrum from an X-ray tube, showing the three main features of the spectrum.
- Explain the continuous range of frequencies and the maximum frequency in the spectrum of the X-rays.
- Derive the formula for the maximum frequency, $f_{\max} = \frac{e\Delta V}{h}$
- Solve problems involving the use of $f_{\max} = \frac{e\Delta V}{h}$

In 1895, German physicist Wilhelm Röntgen (Figure 3.56) was experimenting with a gas discharge tube a darkened laboratory when he observed a card coated with barium platinocyanide that fluoresced with a visible green glow when the tube was switched on (Figure 3.56). Röntgen hypothesised the effect was caused by the emission of electromagnetic rays with a shorter wavelength than light and named the effect **X radiation**. Further investigation revealed the effect was observed even when thick metal sheets and walls were placed between the discharge tube and card, which was unlike any form of radiation that had previously been described. Shortly after his initial discovery, Röntgen used the discharge tube and a photographic plate to produce an image of his wife's hand (Figure 3.56) and concluded that X-rays had a medical use. A year after Röntgen's discovery, more than 1000 scientific articles about the new rays had been published, and X-ray tubes were being utilised in hospitals for medical imaging. For his discovery and investigation, Röntgen was awarded the first Nobel Prize for Physics in 1901.



Wilhelm Roentgen (1845-1923) | Fluorescent green glow of barium platinocyanate in Roentgen's laboratory | X-ray tube positioned above an early photographic plate | First X-ray photograph (1895)

Figure 3.56: Wilhelm Roentgen (1845–1923) and his early discoveries.

X–ray tube

Figure 3.57 shows the components of an X-ray tube which is a device used to produce X-rays for medical and research purposes. X-rays are produced by accelerating electrons to high speeds and colliding them with a target. Electrons are emitted from the cathode when a metal wire **filament** is heated by the flow of electric current. The emitted electrons are then accelerated from cathode to anode through a large potential difference produced by a **high voltage power supply** (not pictured). The high-speed electrons then collide with the target and a very small proportion of the electron kinetic energy (1%) is transformed to X-rays. The remainder of the energy is transformed to heat which is dissipated from the target by cooling fins or a rotating anode (pictured). The cathode and anode are contained in an **evacuated tube** so that the electrons can travel from cathode to anode without colliding with air molecules that reduce their speed and change their direction of motion.

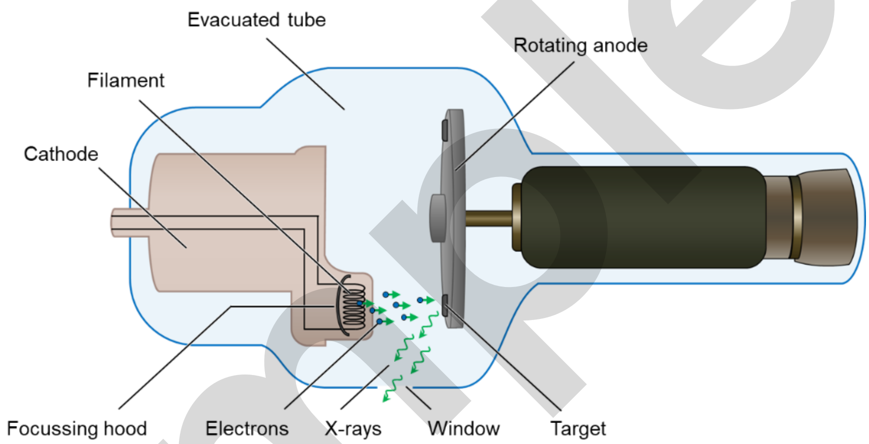


Figure 3.57: Components of a simple X-ray tube.

The emitted X-rays then penetrate the glass window of the evacuated tube and are incident on a patient (Figure 3.58) or apparatus used in scientific research. For a traditional medical or dental X-ray photograph, the X-rays emerging from the tube pass through the body and are detected on a digital sensor, fluorescent screen, or photographic film. The X-rays are absorbed and scattered to varying degrees by different tissue types in the body. This differential absorption and scattering are what produces the brighter and darker regions of the X-ray photograph.

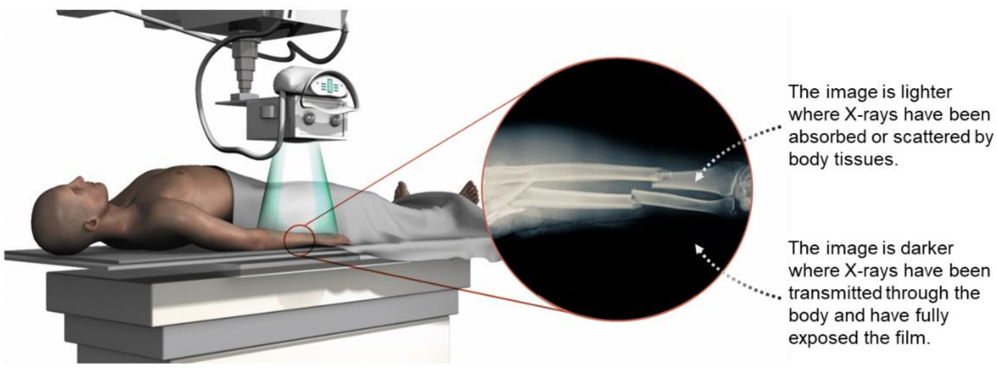


Figure 3.58: X-ray of the arm of a patient.

X–ray spectrum

The photons produced in the X-ray tube have a continuous range of frequencies up to a maximum value which arises from the different interactions of the accelerated electrons with the target. The target is typically composed of a heavy metal element with a high atomic number such as chromium (Z = 24), copper (Z = 29), molybdenum (Z = 42), or tungsten (Z = 74). The high positive charge on the nuclei of target atoms causes the electrons to decelerate, change direction or collide with nuclei as they pass through the target (Figure 3.59). X-rays produced in this way are referred to as **bremsstrahlung** or “braking radiation” as they are produced by the deceleration of electrons.

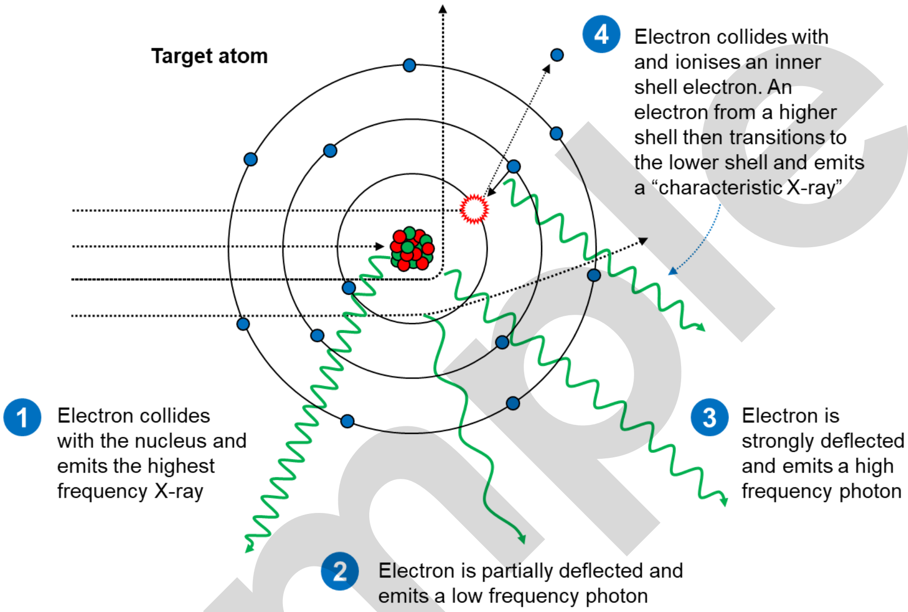


Figure 3.59: Various bremsstrahlung interactions.

Figure 3.60 shows the continuous spectrum of X-rays emitted by an X-ray tube. There are three main features of the spectrum, and each of these is described in the diagram below.

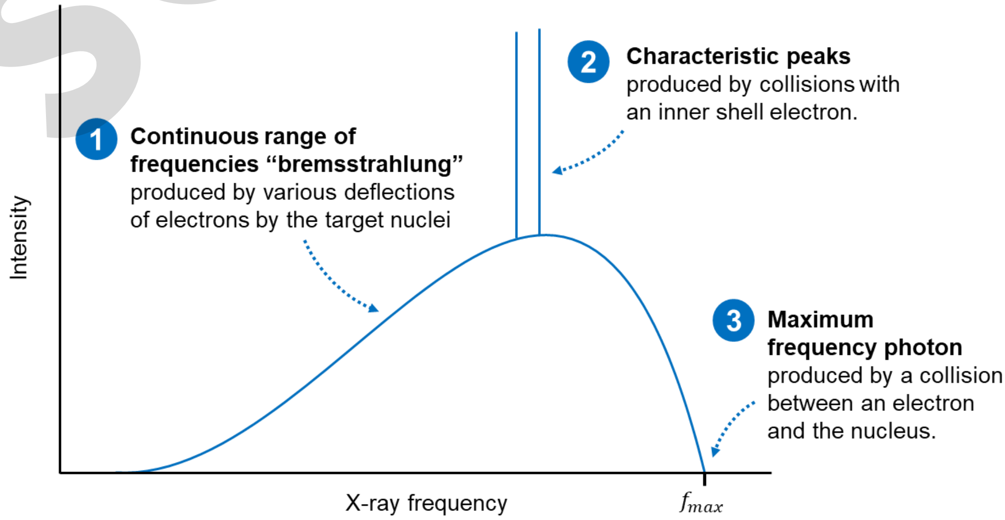


Figure 3.60: X-ray spectrum.

Maximum frequency

The X-rays produced in an X-ray tube have a range of frequencies including a maximum frequency that results from the collision of an electron with the nucleus of a target atom. The collision transfers all of the electron kinetic energy into a photon resulting in the emission of an X-ray with high energy and frequency. The maximum frequency of the emitted X-rays is dependent on the potential difference between the cathode and anode, as shown in Figure 3.61.

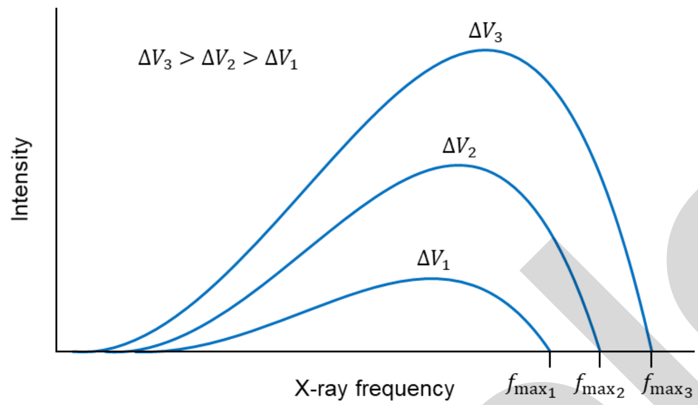


Figure 3.61: Effect of potential difference on f_{max}

The graph shows that the maximum frequency of the emitted X-rays increases with potential difference. As potential difference increases, more work ($e\Delta V$) is done on the electrons, which increases their kinetic energy. An electron that collides directly with the nucleus of a target atom will transform all of its energy ($e\Delta V$) into an X-ray photon, and this property is used to derive a formula to calculate the maximum frequency.

$$\Delta E = hf_{max}$$

$$e\Delta V = hf_{max}$$

$$f_{max} = \frac{e\Delta V}{h}$$

Example 3.27

An X-ray tube operates at 35 kV.

Calculate the maximum frequency of an emitted X-ray.

$$f_{max} = \frac{e\Delta V}{h}$$

$$f_{max} = \frac{1.6 \text{ x } 10^{-19} \text{ x } 35 \text{ x } 10^{3}}{6.63 \text{ x } 10^{-34}}$$

$$f_{max} = 8.45 \text{ x } 10^{18} \text{ Hz}$$

Particles exhibit wave behaviour with a wavelength that depends on the momentum of the particle. This de Broglie wavelength can be determined using the formula $\lambda = \frac{h}{p}$ where h is Planck's constant and p is the momentum of the particles.

The wave behaviour of particles can be demonstrated using a double-slit experiment and the Davisson-Germer experiment.

- Solve problems involving the use of the formula $\lambda = \frac{h}{p}$ for electrons and other particles.
- Describe two-slit interference pattern produced by electrons in double-slit experiments.
- Describe the Davisson-Germer experiment, in which the diffraction of electrons by the surface layers of a crystal lattice was observed.
- Compare the de Broglie wavelength of electrons with the wavelength required to produce the observations of the Davisson-Germer experiment and two-slit interference experiments.

In 1923, French physicist Louis de Broglie* (Figure 3.64) proposed a wave nature for matter.

Figure 3.64: Louis de Broglie (1892–1987)

*De Broglie's surname is pronounced "de-Broy".

De Broglie was fascinated by the wave-particle duality exhibited by light and hypothesised that subatomic particles also possessed wave-particle duality. In his PhD thesis, De Broglie derived a formula to calculate the wavelength of a particle in motion.

Formula	$\lambda = \frac{h}{p}$

Symbol	Variable	SI unit
λ	de Broglie wavelength of the particle	m
h	Planck's constant	J s
p	Momentum of particle	kg m s^{-1}

Example 3.28

Calculate the de Broglie wavelength of a neutron moving at 2 km s^{-1}

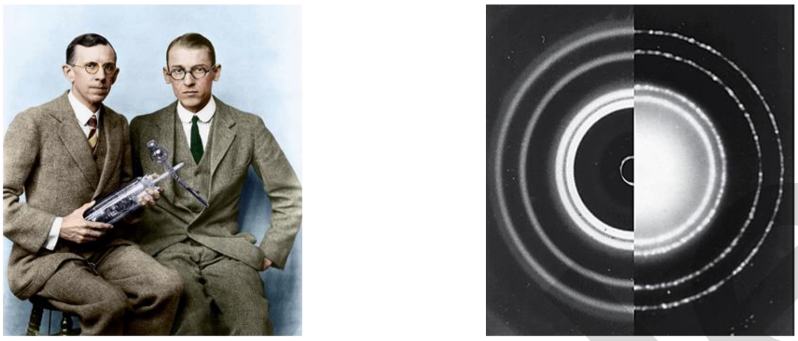
$$\lambda = \frac{h}{p}$$

$$\lambda = \frac{6.63 \times 10^{-34}}{1.675 \times 10^{-27} \times 2 \times 10^{3}}$$

$$\lambda = 1.98 \times 10^{-10} \text{ m}$$

Davisson-Germer experiment

De Broglie's hypothesis received almost immediate experimental confirmation. In 1927, American physicists C. J. Davisson and L. H. Germer (Figure 3.65) discovered that a beam of electrons produced a diffraction pattern when reflected from the surface of a metal crystal. Furthermore, the diffraction pattern was identical to the pattern produced by X-rays with a similar wavelength as shown in Figure 3.65.



Left: Clinton Davisson (1881-1958)
Right: Lester Germer (1896-1971)

Left: Diffraction with 50 pm electrons
Right: Diffraction with 71 pm X-rays

Figure 3.65: Davisson and Germer (left) and diffraction patterns (right).

Davisson and Germer concluded that electrons exhibited a wave nature and devised an experiment to determine the wavelength of an electron which is described in Figure 3.66. The experiment involved firing a low energy (54 eV) beam of electrons at a nickel crystal target. Nickel was chosen as the target since the distance between atoms (d) was known to be 0.22 nm which was comparable to the wavelength of an electron predicted using the de Broglie wavelength formula. The electrons reflected from the crystal surface at different angles and Davisson and Germer moved their detector until the intensity of the reflected beam reached its maximum value which is the position of the first order maxima ($m = 1$). Davisson and Germer measured the angle of the first order maxima and used the grating formula ($dsin\theta = m\lambda$) to determine the wavelength of the electrons.

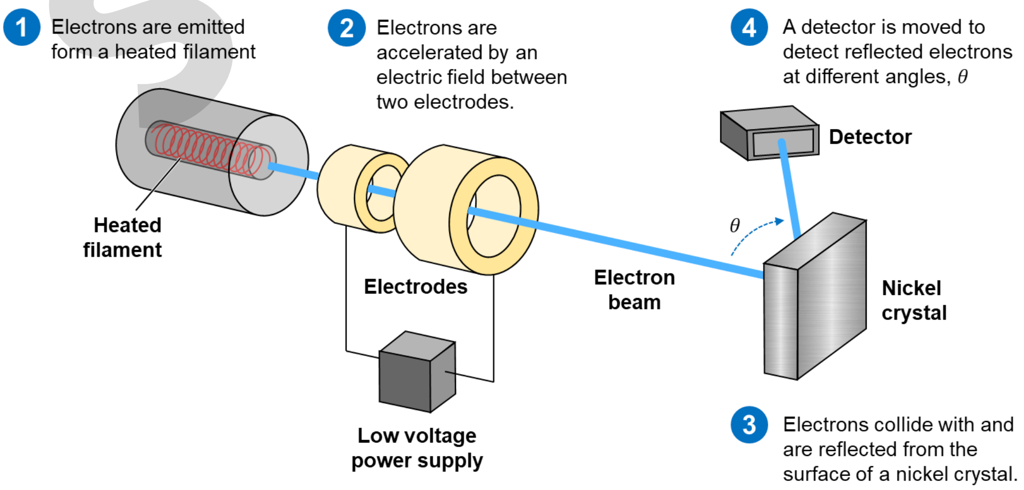


Figure 3.66: Apparatus used in the Davisson-Germer experiment.

3.3: Structure of the atom

A continuous spectrum contains a continuous range of frequencies.

Solid, liquid, or dense gaseous objects radiate a continuous spectrum, which may extend into or beyond the visible region. The process is known as incandescence. The frequency distribution, and hence the dominant colour, depends on the temperature of the object.

- Describe the changes in the spectrum of a filament globe as the temperature of the filament increases.

The light from heated solids, such as a light globe filament, liquids such as molten iron, and dense gaseous objects such as stars, produces a **continuous spectrum** containing a wide range of frequencies of electromagnetic radiation. The continuous range of frequencies of radiation emitted results from the continuous range of oscillating frequencies of the vibrating particles in the dense object. Within the frequency distribution is a **peak wavelength** at which the intensity per wavelength interval is largest, and this wavelength is observed as the dominant colour emitted by the hot object. The frequency distribution, peak wavelength and intensity depend on the temperature of an object. Figure 3.70 shows the continuous spectrum and frequency distribution emitted by the tungsten filament of a light globe at three different temperatures. The intensity is given as a spectral power density which is a measure of the power output per unit area at each wavelength interval.

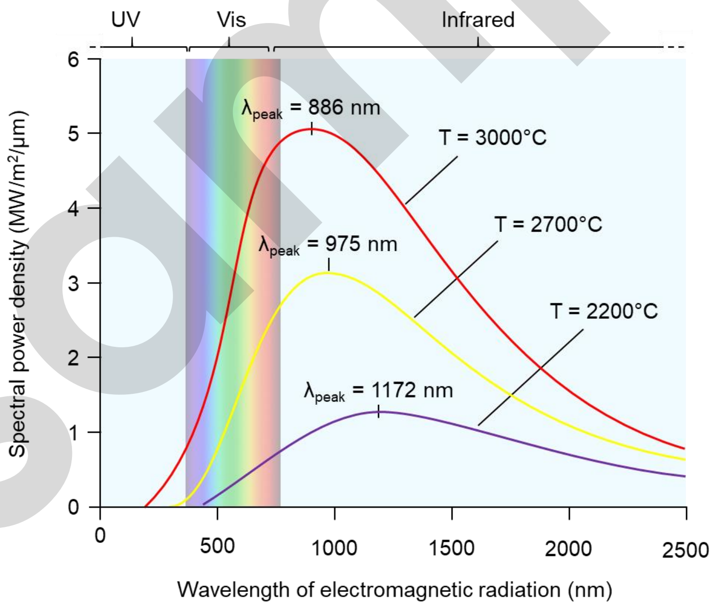


Figure 3.70: Frequency distribution of a filament light globe at different temperatures.

The graph shows that peak wavelength decreases, and peak intensity increases as the temperature is increased. Hence, a light globe filament at 3000°C is hotter and brighter than one of the same size at 2700°C. Furthermore, the graph shows that the intensity of higher frequencies increases with temperature, and this is due to the increase in the average vibrational kinetic energy of the atoms in the filament at higher temperatures.

Atoms can be raised to excited states by heating or by bombardment with light or particles such as electrons.

The heated vapour of a pure element emits light of discrete frequencies, resulting in a line emission spectrum when the light is viewed with a spectrometer.

- Describe the general characteristics of the line emission spectra of elements.
- Explain how the uniqueness of the spectra of elements can be used to identify the presence of an element.
- Explain the production of characteristic X-rays in an X-ray tube.

A continuous spectrum is emitted when solids, liquids and high-density gases are heated. The emitted radiation is due to the oscillations of atoms and molecules, which are primarily governed by the interaction of each atom or molecule with its neighbours. The frequency distribution of the continuous spectrum is solely dependent only temperature and contains no information about the atomic or molecular composition of the object. In contrast, low-density gases emit only discrete wavelengths when energised by light, intense heating, or high-voltage electricity. When this light is analysed through the slit of a spectroscope or spectrometer, a line spectrum is seen rather than a continuous spectrum. Figure 3.71 shows the line spectra emitted when a high voltage is applied to separate discharge tubes containing hydrogen, helium, and neon gases at low pressure.

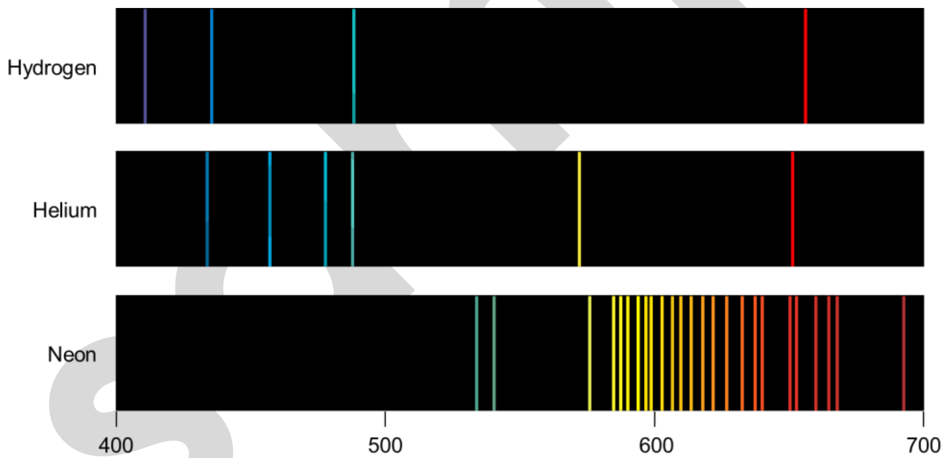


Figure 3.71: Discrete spectra of hydrogen, helium, and neon.

Figure 3.71 shows the discrete spectra emitted by each gas as it appears on the detector of a spectrometer. Each bright line is called a **spectral line** and represents one specific wavelength present in the light emitted by each gas. The discrete spectrum is called a **line emission spectrum** because of its appearance on the detector. A line emission spectrum contains a series of sharp, coloured lines at specific wavelengths with no overlapping lines. Every chemical element and compound emits a unique line emission spectrum which serves as a fingerprint for analysing the chemical composition of materials including soils and minerals, as well as monitoring air pollutants and studying the atmospheres of planets, moons, and stars.

Energy transitions

Before discussing the production of a line emission spectrum, it is necessary to understand that atoms and molecules have different energy states that result from the internal motion of the particles in an atom. An atom is in its lowest energy state, called **ground state,** when its electrons have their lowest energy and is in an **excited state** when one or more electrons are in a higher energy state. An atom can undergo a transition from one energy state to another by emitting or absorbing a photon whose energy is equal to the energy difference between the two energy states. The absorption of a photon raises the atom to a higher-energy state, and the emission of a photon causes an atom to transition to a lower-energy state, as shown in Figure 3.72. Atoms can also transition from lower-energy state to a higher energy state by absorbing energy in a collision with other another particle in a process called **collisional excitation**. The excited atoms quickly transition down to lower-energy states, eventually ending in the ground state, as shown in Figure 3.72.

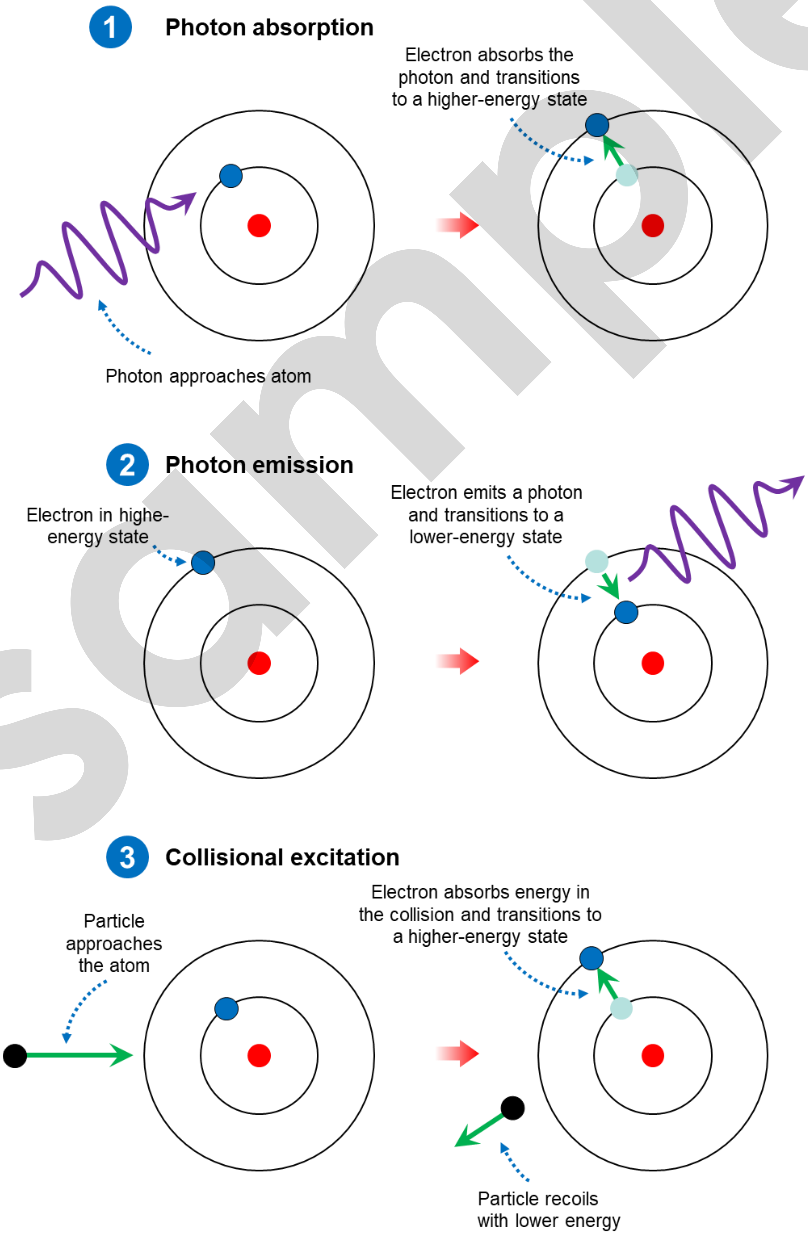


Figure 3.72: Photon absorption, photon emission and collisional excitation.

Emission spectrum

A line emission spectrum is observed when a low-density gas is energised by light, intense heating, or high-voltage electricity. On an atomic scale, the transfer of energy through collisions between particles or the absorption of light causes the atoms and molecules of the low-density gas to transition to an excited state as depicted in Figure 3.73. The atoms remain in the excited state for an average time of a few nanoseconds before returning to a lower energy state. By the law of conservation of energy, the atom emits the energy difference between the two energy states as a photon, as shown in Figure 3.73.

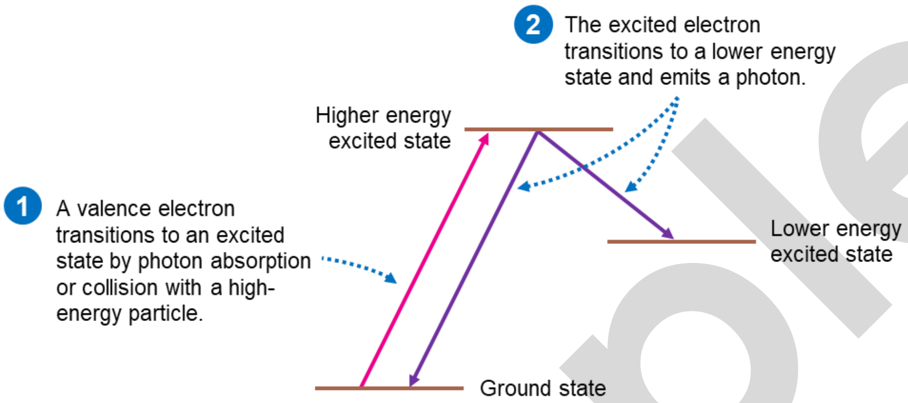


Figure 3.73: Generation of an emission spectrum.

Atoms and molecules have many excited states which allow valence electrons to emit a wide array of photons, each with a specific wavelength, as they transition between different energy states. The discrete wavelengths emitted by the valence electrons take the form of the spectral lines in the line emission spectrum of the element or compound. Figure 3.74 shows some energy transitions in the element sodium that result in the emission of visible light.

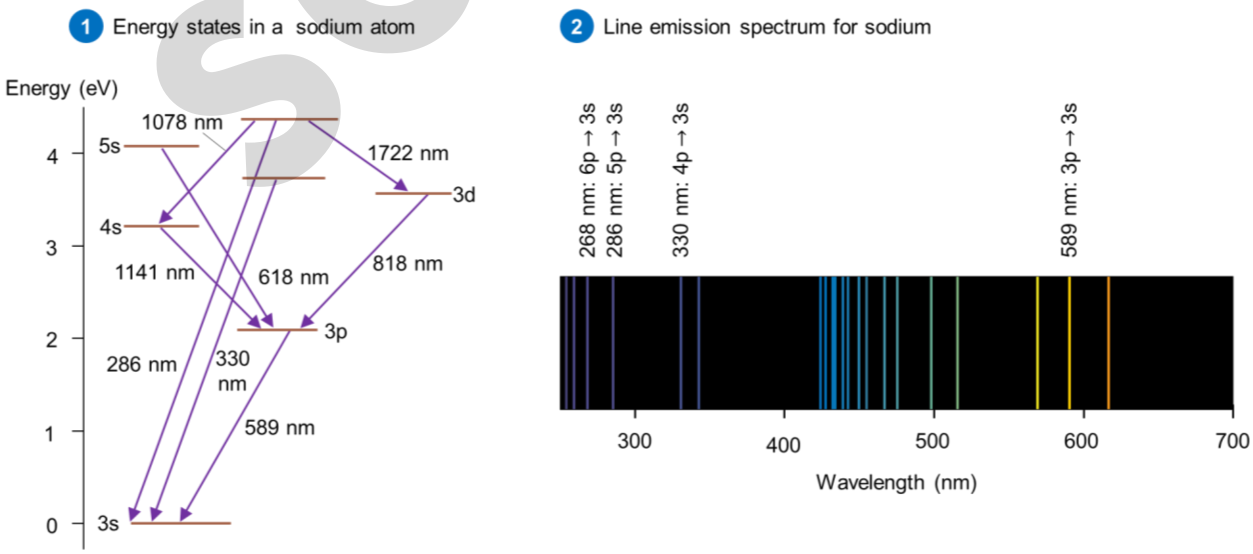


Figure 3.74: Energy states and line emission spectrum of sodium.

Characteristic X-rays

The line emission spectrum of an element is often called its **optical spectrum** as the spectral lines correspond to the emission of photons with energies ranging from 2-3 eV and wavelengths in the visible region of the electromagnetic spectrum. These photons are emitted when electrons in the outermost shell, called **valence electrons**, transition from an excited state to a lower-energy state in an atom or molecule. However, photons can also be emitted when electrons transition from an outer shell to an inner shell in an atom. Recall from chapter 3.2 that X-rays are produced in an X-ray tube when high-speed electrons collide with a metal target. The bremsstrahlung interactions of electrons with target nuclei produce a continuous spectrum of X-rays with high-intensity peaks at particular frequencies. These peaks, known as **characteristic X-rays**, are produced when high-speed electrons collide with inner shell electrons in the target atoms, as shown in Figure 3.75.

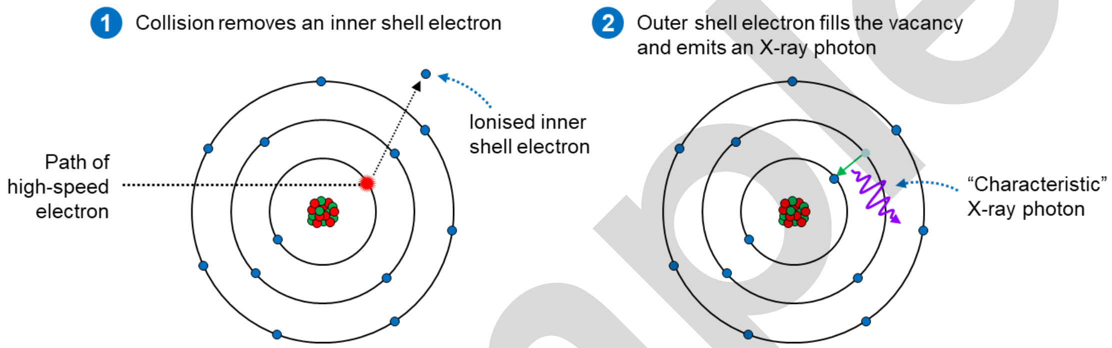


Figure 3.75: Production of characteristic X-rays in atoms.

The collision creates a vacancy in the inner shell that is quickly filled by an electron from an outer shell. In heavy elements such as copper, chromium, molybdenum or tungsten, the difference in energy between the inner and outer shells is very large, typically 10 keV. Consequently, the photon emitted has a wavelength in the X-ray region of the electromagnetic spectrum. In most cases, more than one characteristic X-ray is emitted as the inner shell may be filled by an electron in any higher energy shell. Figure 3.76 shows the production of characteristic X-rays in copper atoms.

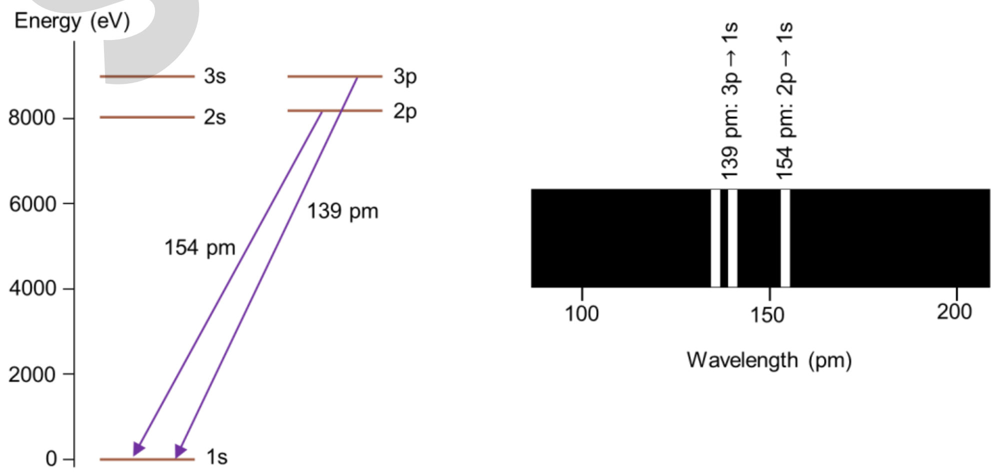


Figure 3.76: Production of characteristic X-rays in copper.

Energy levels

Bohr's hypothesis of energy levels in atoms was revolutionary, and he set out to find experimental evidence by investigating the line emission spectrum of hydrogen. Bohr pictured the energy levels in hydrogen in terms of the electron revolving in various circular orbits around the proton and that only certain orbit radii were permitted. Bohr reasoned that the four lines in the optical emission spectrum of hydrogen resulted from the emission of four photons of different energies and wavelengths and that each photon was emitted when the electron transitioned from a higher-energy level to a lower-energy level in the hydrogen atom as depicted in Figure 3.78.

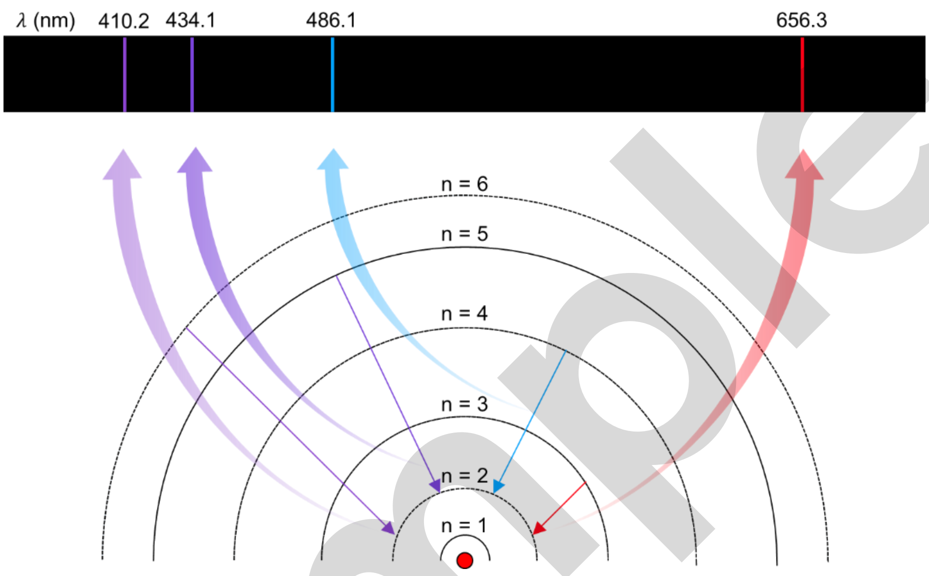


Figure 3.78: Explaining the line emission spectra using

Using the law of conservation of energy, Bohr showed that the energy of an emitted photon (hf) was equal to the energy difference between the initial and final levels.

$$hf = E_i - E_f$$

Example 3.29

A photon with a wavelength of 656.3 nm is emitted when an electron transitions from n = 3 to n = 2. Calculate the difference in energy between these two energy levels in a hydrogen atom in eV.

$$E_i - E_f = hf$$

$$E_i - E_f = h\frac{c}{\lambda}$$

$$E_i - E_f = \frac{6.63 \text{ x } 10^{-34} \text{ x } 3 \text{ x } 10^{8}}{656.3 \text{ x } 10^{-9} \text{ x } 1.6 \text{ x } 10^{-19}}$$

$$E_i - E_f = 1.89 \text{ eV}$$

When light with a continuous spectrum is incident on a gas of an element, discrete frequencies of light are absorbed, resulting in a line absorption spectrum.

The frequencies of the absorption lines are a subset of those in the line emission spectrum of the same element.

- Describe the line absorption spectrum of an atom, for example, hydrogen.
- On an energy-level diagram, draw transitions corresponding to the line absorption spectrum of hydrogen.
- Explain why there are no absorption lines in the visible region for hydrogen at room temperature.
- Account for the presence of absorption lines (Fraunhofer lines) in the Sun's spectrum.

Recall from Figure 3.72 that electrons transition to a higher-energy level when they absorb a photon with energy equal to the difference between two energy levels in the atom. When a continuous spectrum of light is transmitted through a cool*, low-pressure gas, some wavelengths are absorbed, and these appear as dark lines on the detector or screen when the light is analysed through the slit of a spectroscope or spectrometer as shown in Figure 3.84.

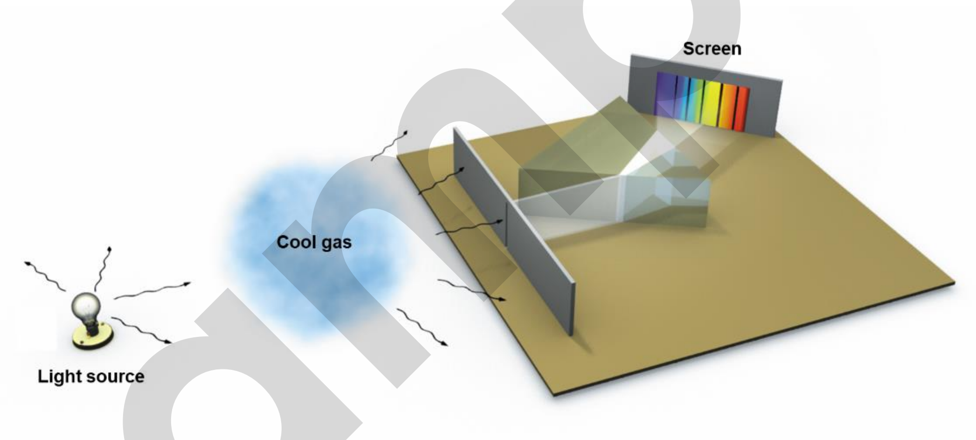


Figure 3.84: Continuous spectrum transmitted through a cool, low pressure gas.

The resulting spectrum is called a **line absorption spectrum,** and the dark lines are called **absorption lines.** Each absorption line corresponds to one wavelength absorbed from the continuous spectrum by atoms and molecules the gaseous sample, and these are used in the identification of elements and compounds in a sample. Figure 3.85 shows the line absorption spectrum of helium.

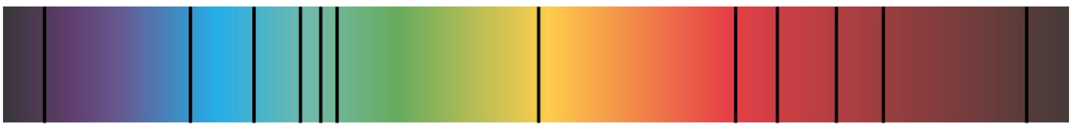


Figure 3.85: Line absorption spectrum of helium.

*When a gas is cool, the electrons of atoms and molecules in the sample occupy the lowest energy level and are primed for absorbing wavelengths from the continuous spectrum. If the gas were hot, electrons would already occupy excited states, and not all wavelengths would be absorbed from the continuous spectrum.

Absorption and emission spectra

The black lines in the absorption spectrum appear in the same position as the coloured lines in the emission spectrum of an element or compound. However, there is an essential difference between the emission and absorption spectra of an element or compound. Every wavelength absorbed by the element or compound is also emitted, but not every emitted wavelength is absorbed. As a result, the wavelengths in the absorption spectrum appear as a subset of the wavelengths in the emission spectrum. Figure 3.86 shows the absorption and emission spectra of sodium. The diagram shows that all absorption wavelengths are present in the emission spectrum, but there are many emission lines for which no absorption occurs.

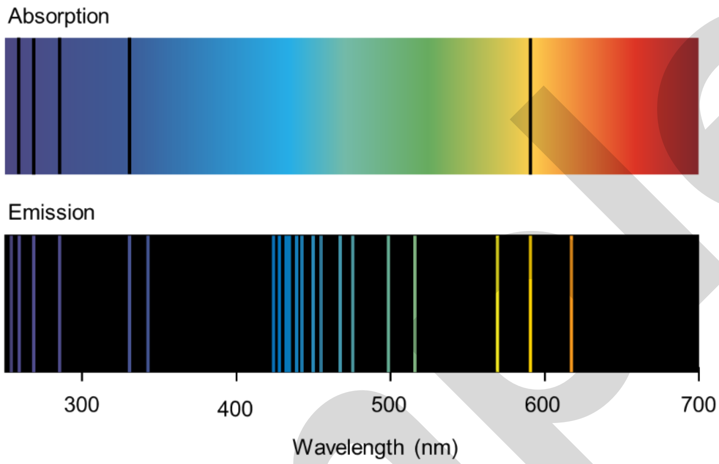


Figure 3.86: Line absorption and emission spectra of sodium.

The elemental composition of gaseous mixtures such as the outer atmosphere of a star or planet can be determined by comparing the position of the absorption lines in the absorption spectrum of the star with the position of the emission lines in the emission spectra of the elements. Figure 3.87 shows the absorption spectrum of the star Sirius A which contains hydrogen, helium, and sodium.

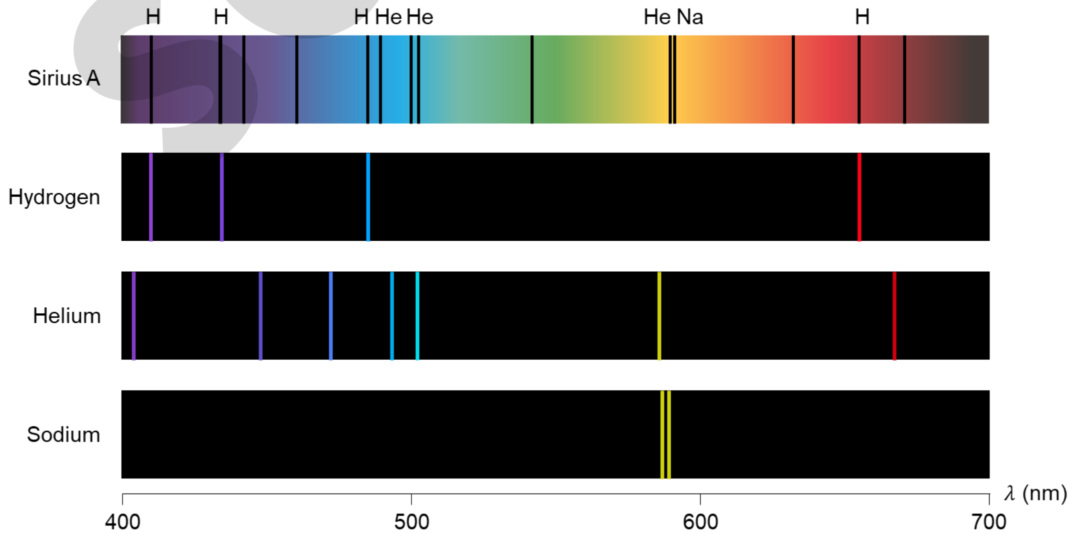


Figure 3.87: Line absorption of Sirius A.

Line absorption spectrum of hydrogen

The line absorption spectrum of hydrogen contains four absorption lines at wavelengths corresponding to transitions from n = 2 to n = 3, 4, 5 and 6, as shown in Figure 3.88.

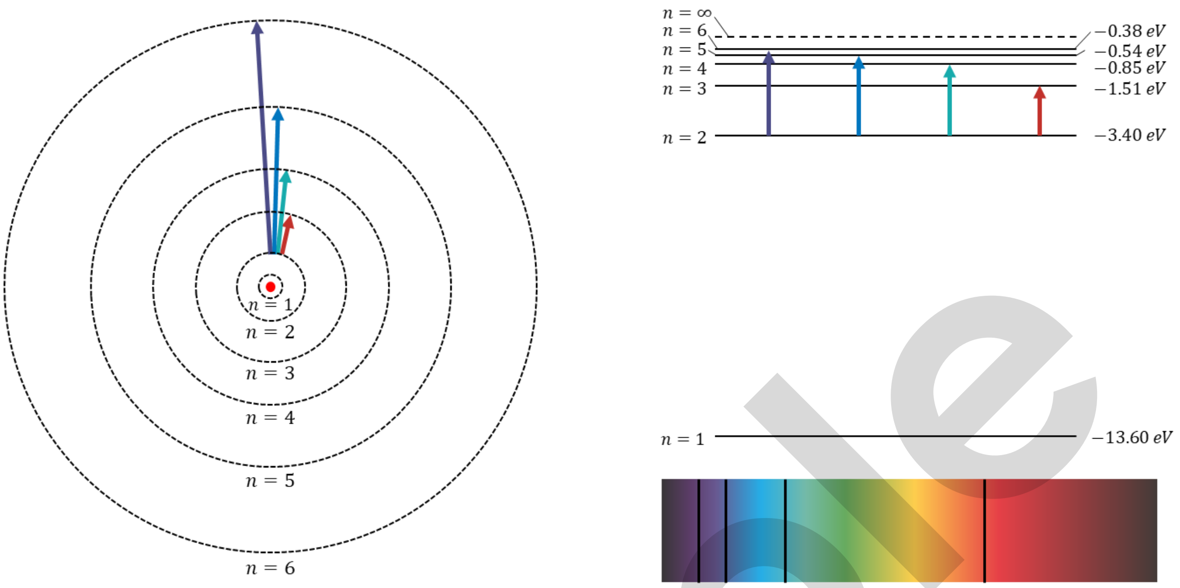


Figure 3.88: Transitions corresponding to the line absorption spectrum of hydrogen.

The presence of the four absorption lines is dependent on the temperature of the hydrogen gas. Figure 3.89 shows the absorption spectrum of hydrogen at room temperature and a higher temperature (between 4,000 and 12,000 K). The diagram shows that the absorption lines are not present in the absorption spectrum of hydrogen at room temperature. This is because hydrogen atoms are in ground state (n = 1) at room temperature and the electron must be in the first excited state (n = 2) to absorb photons with wavelengths in the visible region of the electromagnetic spectrum as shown in Figure 3.88. As the temperature is increased, the electron may have sufficient energy to transition to n = 2, where it can absorb wavelengths of visible light and produce the line absorption spectrum shown in Figure 3.89.

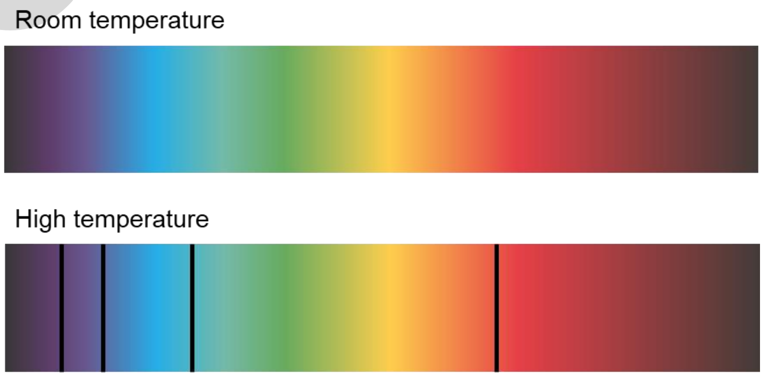


Figure 3.89: Line absorption spectrum of hydrogen at different temperatures.

Fraunhofer lines

The sun emits a continuous spectrum of electromagnetic radiation from its surface, and this radiation is transmitted through the atmosphere of the star. The atmosphere of the sun contains several chemical elements, and the atoms of these elements absorb specific wavelengths from the continuous spectrum resulting in several absorption lines in the solar spectrum (Figure 3.90).

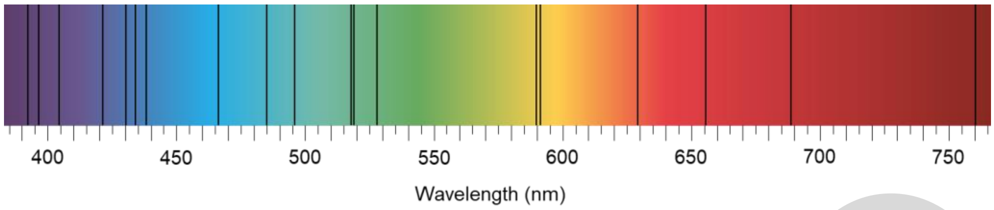


Figure 3.90: Absorption lines in the solar spectrum.

The absorption lines in the solar spectrum were first investigated and described by German physicist Joseph von Fraunhofer between 1814 and 1815 and are known as **Fraunhofer lines**. Fraunhofer is credited with the discovery of nearly 600 lines in the absorption spectrum of sunlight, and some of these are depicted in Figure 3.91. The technique pioneered by Fraunhofer has since been used to investigate the elemental composition of stars, planets, and moons.

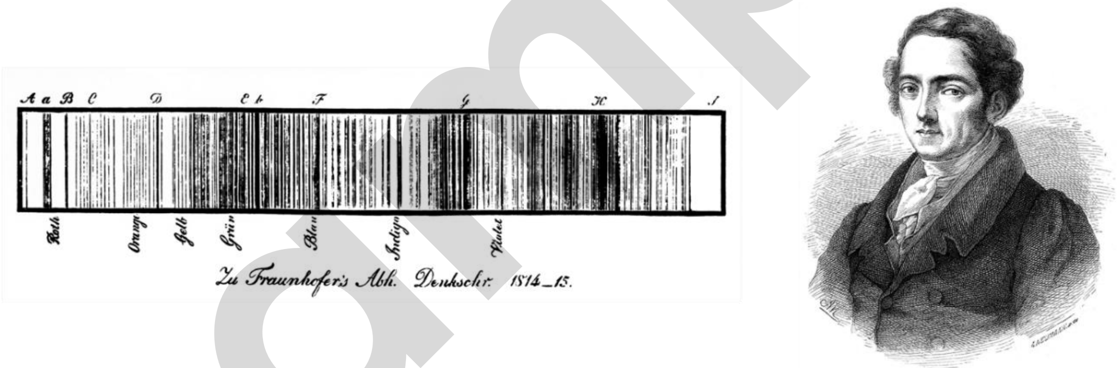


Figure 3.91: Fraunhofer lines (left). Joseph Fraunhofer (1787–1826, right).

Four decades after Fraunhofer's discovery, scientists noted that Fraunhofer lines coincided with the emission lines in the spectra of heated elements, and this discovery permitted the identification of some chemical elements present in the atmosphere on the sun (Figure 3.92). Careful analysis revealed the presence of hydrogen (H), oxygen (O_2), sodium (Na), calcium (Ca) and iron (Fe).

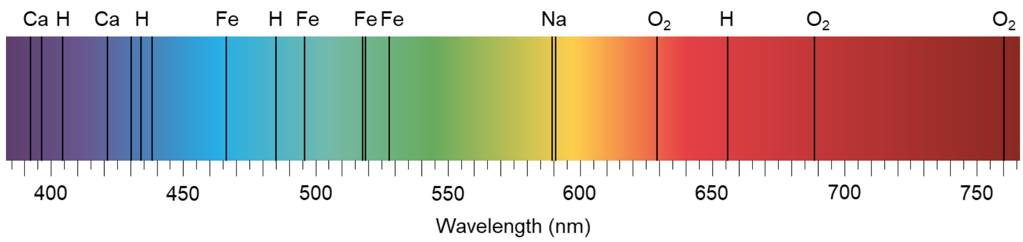


Figure 3.92: Chemical elements responsible for Fraunhofer lines.

When an atom absorbs a photon, it is elevated to an 'excited state', which has a higher energy. Excited states are generally short-lived, and the atom returns spontaneously to its ground state, often by emitting a series of lower-energy photons.

'Fluorescence' is the process where an atom absorbs a photon to reach an excited state, but then reverts to the ground state emitting two or more photons with lower energy and longer wavelength.

- Draw, on an energy-level diagram of, for example, hydrogen, the production of multiple photons via fluorescence.
- Analyse and explain the characteristic wavelengths, fluorescence, and line spectra for elements other than hydrogen using electron energy levels.

Fluorescence is a process in which an atom absorbs a higher energy photon to reach an excited state and then reverts to ground state through the emission of two or more photons with lower energy and longer wavelengths. Figure 3.93 illustrates the process of fluorescence in hydrogen. The atom in ground state absorbs a high energy photon (12.75 eV), and this causes the electron to transition to the third excited state, n = 4. The atom then reverts to the ground state in three different energy transitions, each resulting in the emission of a photon with lower energy and a longer wavelength than the photon that was absorbed. In hydrogen, fluorescence only occurs if the photon absorbed has an amount of energy that promotes the electron to transition to an energy level above n = 2. Transitions to n = 2 do not produce fluorescence in hydrogen as only one transition is possible as the electron returns to ground state.

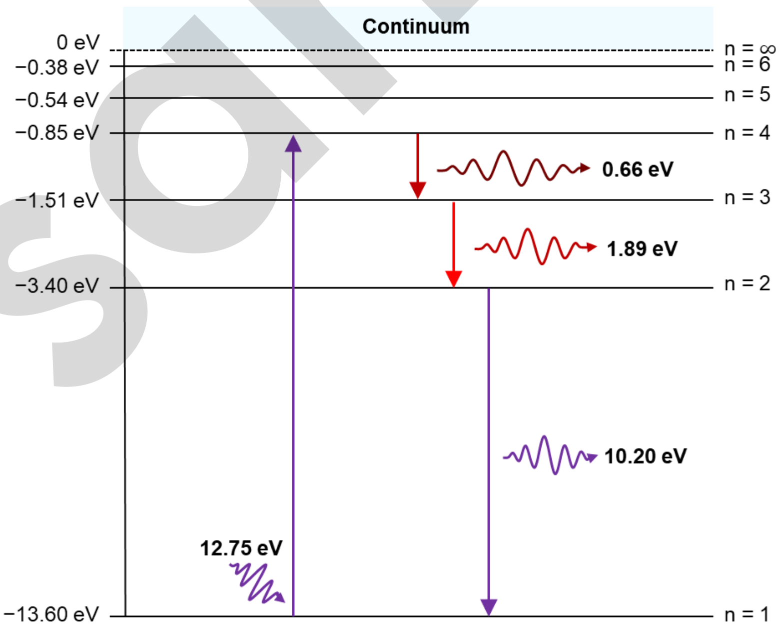


Figure 3.93: Fluorescence in hydrogen.

Fluorescence occurs in living and non-living things and has many applications in medicine, mineralogy, forensics, molecular biology, and counterfeit detection.

Lasers use the process of stimulated emission to produce electromagnetic radiation. In many lasers, stimulated emission occurs from atoms that are in a higher-energy state.

A population inversion is produced in a set of atoms whenever there are more atoms in a higher-energy state than in a lower-energy state. For practical systems, the higher-energy state must be metastable if a population inversion is to be produced.

The energy carried by a laser beam is concentrated in a small area and can travel efficiently over large distances, giving laser radiation a far greater potential to cause injury than light from other sources.

- Explain how stimulated emission can produce coherent light in a laser.
- Explain the conditions required for stimulated emission to predominate over absorption when light is incident on a set of atoms.
- Describe the useful properties of laser light (i.e. it is coherent and monochromatic and may be of high intensity).
- Discuss the requirements for the safe handling of lasers.

A laser produces a very narrow, intense beam of coherent light through the process of stimulated emission. The word laser is an acronym: **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation, but the conventional spelling is "laser". Figure 3.96 shows the main components of a laser.

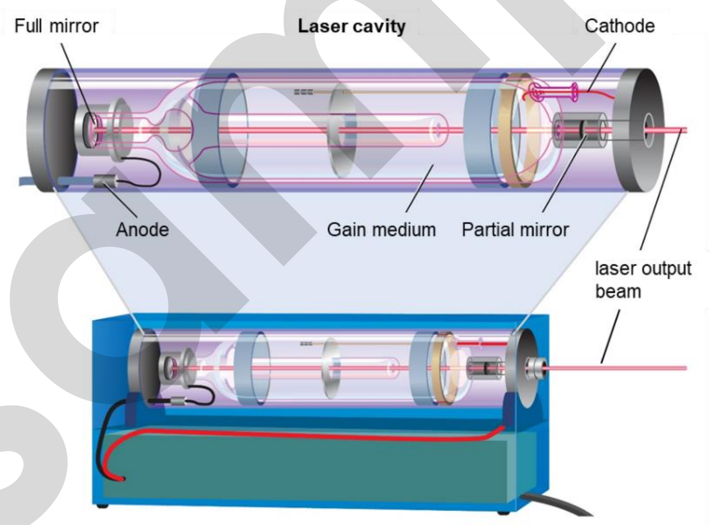


Figure 3.96: Components of a laser.

A laser has a **gain medium** containing atoms or molecules that emit light by stimulated emission. The **anode** and **cathode** are connected to a potential difference, called **the pump**, that does work on the atoms in the gain medium and raises a large proportion to excited states. The atoms emit photons through stimulated emission, and these photons are reflected at each end of the laser cavity by two mirrors. The **full mirror** reflects all photons into the laser cavity to allow for the amplification of light by stimulated emission and constructive interference. The **partial mirror** is partially transparent and permits the transmission of 1-2% of photons in the cavity as a narrow output beam.

3.4: Standard Model

The Standard Model suggests that there are three fundamental types of particles: gauge bosons, leptons, and quarks.

The Standard Model identifies four fundamental forces: electromagnetic, weak nuclear, strong nuclear, and gravitational.

Gauge bosons are particles which mediate the four fundamental forces. They are often called 'exchange particles'.

The gauge boson for gravitational forces, the graviton, is still to be discovered.

Leptons, such as electrons, are particles that are not affected by the strong nuclear force.

Quarks are fractionally charged particles that are affected by all of the fundamental forces.

Quarks combine to form composite particles and are never directly observed or found in isolation.

There are six types of quark, with different properties, such as mass and charge. Each quark has a charge of either $+2/3$ or $-1/3$.

- Describe the electromagnetic, weak nuclear, and strong nuclear forces in terms of gauge bosons.
- Distinguish between the three types of fundamental particles.

The **Standard Model** is a scientific theory that describes and classifies the fundamental particles and forces in the universe. A fundamental particle has no known substructure, meaning that it is not composed of smaller particles. The Standard Model identifies three types* of fundamental particles called **quarks**, **leptons**, and **gauge bosons** (Figure 3.99).

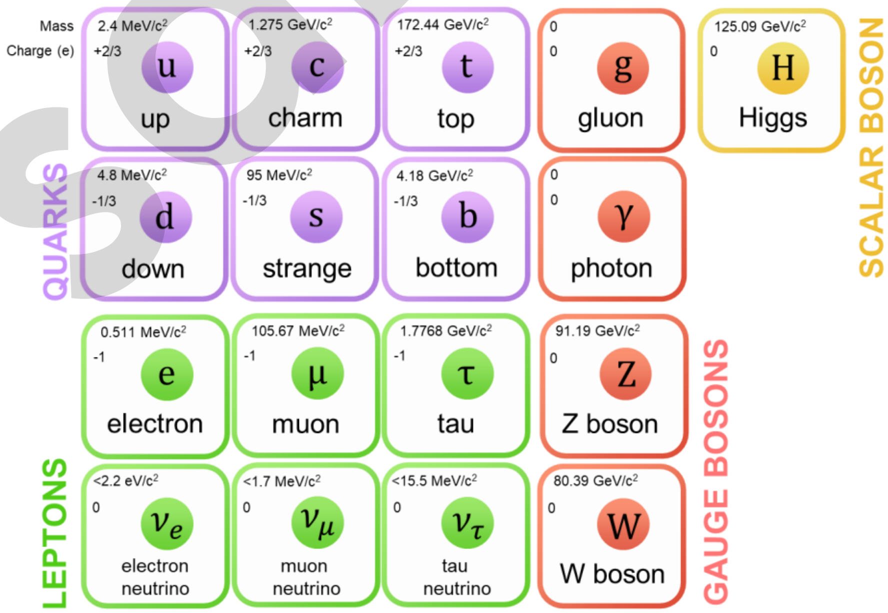
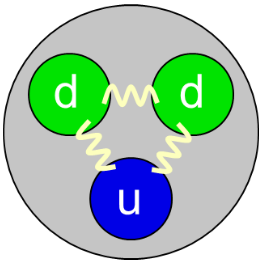


Figure 3.99: Fundamental particles included in the Standard Model.

*There are four types of fundamental particles but Scalar bosons such as the Higgs Boson are not described in this course.

Question

The diagram below shows the internal structure of a neutron.



A neutron contains two down quarks and an up quark.

(a) Use a calculation to show that neutrons are electrically neutral.

(1 mark) KA4

(b) The three quarks are held together by the strong nuclear force.

Describe the strong nuclear force using the concept of exchange particles.

(2 marks) KA1

(c) A neutron decays radioactively into a proton and a W boson.

(1) Identify the fundamental force involved in this radioactive decay.

(1 mark) KA2

(2) The proton is composed of two up quarks and a down quark.

Use a calculation to show that a proton has a charge of $+1e$.

(1 mark) KA4

(3) The W boson decays to an electron and electron antineutrino.

Classify the products as quarks, leptons, or gauge bosons.

(1 mark) KA2

(4) The electron and proton produced in the decay are attracted to one another.

Name the fundamental force between the electron and proton and identify the gauge boson that mediates the attractive force.

(2 marks) KA2

All other composite matter particles, such as atoms, are thought to be combinations of quarks and leptons.

Baryons are composite particles that consist of a combination of three quarks.

Antiquarks have the opposite charge to their quark equivalent. Quarks and antiquarks can form particles called mesons.

- Describe how protons, neutrons, and other baryons can be formed from different combinations of quarks.

A composite particle is composed of two or more fundamental particles. The most common types of composite particles are hadrons, known as **baryons** and **mesons**.

Baryons

Baryons are composite particles composed of three quarks. Examples of baryons include the proton, neutron, lambda, and the omega (Figure 3.101).

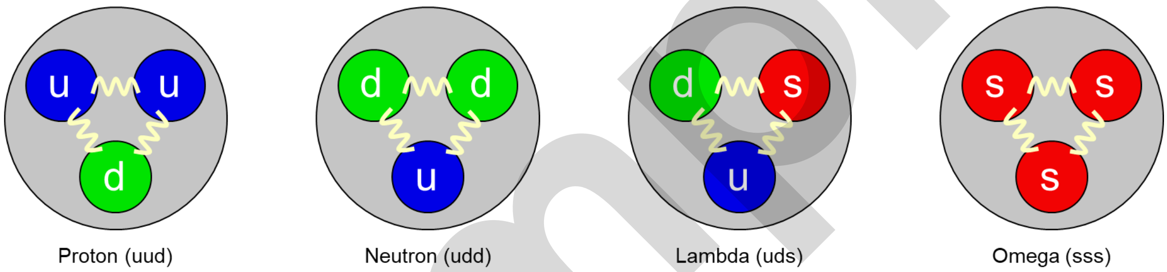


Figure 3.101: Examples of baryons.

Some baryons and their physical properties are identified in the table below.

Baryon	Symbol	Composition	Charge (*e*)	Lifetime (s)	Mass (MeV/c²)
Proton	p	uud	+1	Stable	938.27
Neutron	n	udd	0	880	939.57
Lambda	Λ^0	uds	0	2.6 x 10^{-10}	1115.68
Omega	Ω^-	sss	−1	8.2 x 10^{-11}	1672.45
Sigma plus	Σ^+	uus	+1	8.0 x 10^{-11}	1189.37
Sigma minus	Σ^-	dds	−1	1.5 x 10^{-10}	1197.45
Charmed sigma	Σ_c^0	ddc	0	3.0 x 10^{-22}	2453.76
Bottom sigma	Σ_b^+	uud	+1	unknown	5807.70
Neutral cascade	Ξ^0	uss	0	2.9 x 10^{-10}	1314.86
Cascade minus	Ξ^-	dss	−1	1.6 x 10^{-10}	1321.71

Mesons

Mesons are composite particles composed of one quark and one antiquark. Examples of mesons include the pion, kaon, B, D, eta, and rho (Figure 3.103).

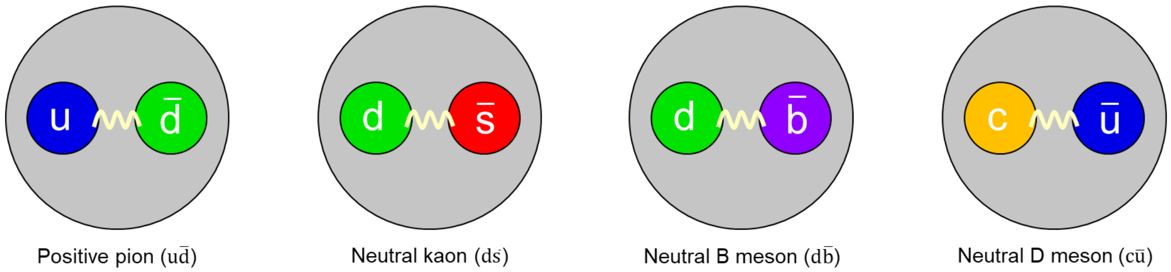


Figure 3.103: Examples of mesons.

Some mesons and their physical properties are identified in the table below.

Meson	Symbol	Composition	Charge (*e*)	Lifetime (s)	Mass (MeV/c^2)
Positive pion	π^+	$u\bar{d}$	+1	2.6 x 10^{-8}	139.57
Positive kaon	K^+	$u\bar{s}$	+1	1.2 x 10^{-8}	493.68
Neutral kaon	K^0	$d\bar{s}$	0	1.2 x 10^{-8}	497.61
Neutral D	D^0	$c\bar{u}$	0	4.1 x 10^{-13}	1864.84
Positive D	D^+	$c\bar{d}$	+1	1.0 x 10^{-12}	1869.61
Strange D	D_s^+	$c\bar{s}$	+1	5.0 x 10^{-13}	1968.30
Charmed eta	η_c	$c\bar{c}$	0	2.0 x 10^{-23}	2983.60
Charged rho	ρ^+	$u\bar{d}$	+1	4.5 x 10^{-24}	775.40
Neutral B	B^0	$d\bar{b}$	0	1.5 x 10^{-12}	5279.58

The charge on a baryon or meson is determined by summing the charges on its quarks.

Example 3.31

A proton (p) is a baryon composed of two up quarks (+2/3*e*) and one down quark (−1/3*e*) and a positive pion (π^+) is a meson composed of one up quark and an antidown quark.

Calculate the electric charge on each particle.

$$p = \left(+\frac{2}{3}\right) + \left(+\frac{2}{3}\right) + \left(-\frac{1}{3}\right) = +1$$

$$\pi^+ = \left(+\frac{2}{3}\right) + \left(+\frac{1}{3}\right) = +1$$

Conservation laws

A study of particle interactions has revealed that lepton number (L), baryon number (B), and electric charge (e) are all conserved in a particle reaction or decay. These conservation laws explain why some reactions occur, and others do not and are used when predicting the outcome of a reaction.

Example 3.32

In beta-minus decay, a neutron decays to a proton, electron, and electron antineutrino.

	n	→	p	+	e^-	+	$\bar{\nu}_e$
L	0	→	0		1		−1
B	1	→	1		0		0
e	0	→	+1		−1		0

Lepton number, baryon number and electric charge are all conserved, indicating a valid reaction.

Example 3.33

In negative kaon (meson) reacts with a proton forming a positive kaon and an antiproton.

	K^-	+	p	→	K^+	+	$\bar{p}$
L	0		0	→	0		0
B	0		1	→	0		−1
e	−1		+1	→	+1		−1

Baryon number is not conserved, indicating an invalid reaction that does not occur.

Example 3.34

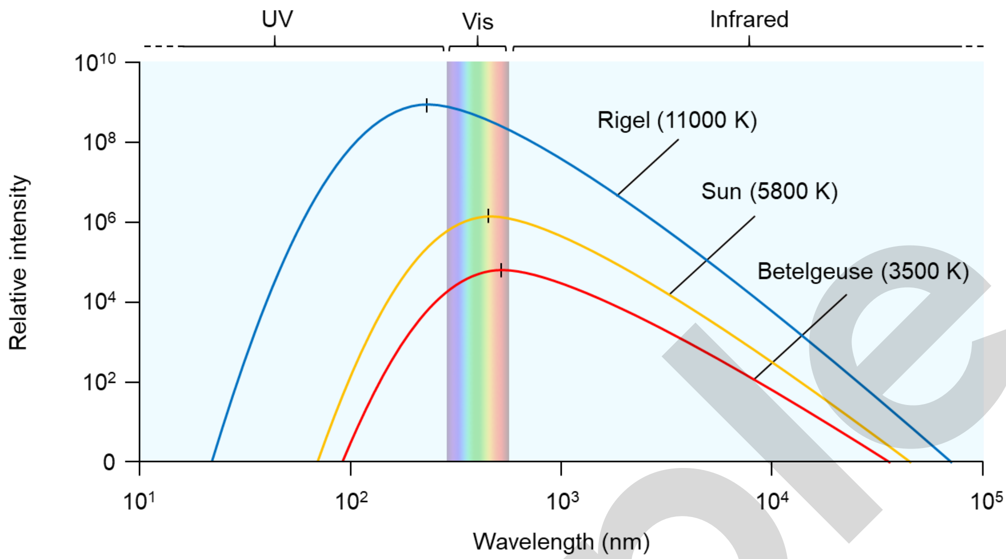
A muon decays into a muon neutrino, electron, and anti-electron neutrino.

	μ^-	→	ν_μ	+	e^-	+	$\bar{\nu}_e$
L	1	→	1		1		−1
B	0	→	0		0		0
e	−1	→	0		−1		0
L_e	0	→	0		1		−1
L_μ	1	→	1		0		0

All conservation laws are satisfied indicating a valid reaction.

Question 1

The diagram below shows the continuous spectrum of electromagnetic radiation emitted by three stars in the Milky Way galaxy.



(a) Describe how the frequency distribution and dominant colour of the continuous spectrum radiated by a star depend on its temperature.

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____ (2 marks) **KA2**

(b) Starlight is produced by the radioactive decay of elements in the core of the star.

One type of radioactive decay is described in the equation below.

	p	$\rightarrow$	n	+	e^+	+	ν_e	
L		$\rightarrow$						
B		$\rightarrow$						
e		$\rightarrow$						

(1) Complete the table and determine if this decay is possible.

____ (3 marks) **KA1**

(2) The W boson is implicated in this decay.

Name the fundamental force mediated by the W boson.

____ (1 mark) **KA1**

Question 4

Read the following passage:

The South Australian Health and Medical Institute (SAHMRI) is a health and medical research institute that focuses on translating high-quality research into practical health improvements for patients in the community. SAHMRI is home to more than 700 researchers, students and business partners working together to tackle several public health challenges.

Researchers at SAHMRI are focusing their efforts on developing and pioneering new treatments to transform innovative health and medical research into practical benefits for patients and the community. The evidence generated at SAHMRI is being utilised to advance public health policy, and the results of clinical trials are informing future research activities across the globe. In addition, the SAHMRI Business Development and Entrepreneurship platform is translating promising research into high impact treatments and therapies; building a community of entrepreneurial researchers.

SAHMRI recently partnered with Bellberry Limited to establish the Bellberry Molecular Imaging Program. The project utilises a cyclotron to develop radiopharmaceuticals to study the progression of diseases ranging from bone, breast and prostate cancers, through to Parkinson's Disease, Epilepsy, and Alzheimer's Disease. The diagnostic agents produced will enhance SAHMRI's ability to deliver improved healthcare, clinical trial capacity and translational health outcomes.

Using the information above, describe examples of how the research conducted by SAHMRI and its partners demonstrates science as a human endeavour.

(6 marks) **KA3**

<table>
<tr><td rowspan="2">243</td><td>(a)</td><td>Zero, because the bottom and antibottom quarks have the opposite charge.</td><td>1</td></tr>
<tr><td>(b)</td><td>$E = \Delta mc^2$
$\Delta m = \frac{E}{c^2}$
$\Delta m = \frac{(8358.75 \text{ x } 10^6 \text{ x } 1.6 \text{ x } 10^{-19})}{(3 \text{ x } 10^8)^2}$
$\Delta m = 1.486 \text{ x } 10^{-26}$ kg
$m = \frac{\Delta m}{2}$
$m = \frac{1.486 \text{ x } 10^{-26}}{2}$
$m = 7.43 \text{ x } 10^{-27}$ kg</td><td>

1
1

1
1</td></tr>
<tr><td rowspan="2">244</td><td>(a)</td><td><table>
<tr><td></td><td>p</td><td>→</td><td>n</td><td>+</td><td>e^+</td><td>+</td><td>ν_e</td></tr>
<tr><td>L</td><td>0</td><td>→</td><td>0</td><td></td><td>−1</td><td></td><td>1</td></tr>
<tr><td>B</td><td>1</td><td>→</td><td>1</td><td></td><td>0</td><td></td><td>0</td></tr>
<tr><td>e</td><td>+1</td><td>→</td><td>0</td><td></td><td>+1</td><td></td><td>0</td></tr>
</table>
The decay is possible as all conservation laws are satisfied.</td><td>3</td></tr>
<tr><td>(b)</td><td>$E = \Delta mc^2$
$E = (9.11 \text{ x } 10^{-31}) \text{ x } (3 \text{ x } 10^8)^2$
$E = 8.20 \text{ x } 10^{-14}$ J
$E = \frac{8.20 \text{ x } 10^{-14}}{1.6 \text{ x } 10^{-19}}$
$E = 5.12 \text{ x } 10^5 \ eV$
$E = \frac{5.12 \text{ x } 10^5}{1 \text{ x } 10^3}$
$E = 512.4 \ keV$</td><td>
1
1

1

1</td></tr>
<tr><td rowspan="2">245</td><td>(a)</td><td>Meson;
as baryon and lepton number would not be conserved if particle D were a baryon or lepton.</td><td>1</td></tr>
<tr><td>(b)</td><td>$E = \Delta mc^2$
$\Delta m = \frac{E}{c^2}$
$\Delta m = \frac{(211.32 \text{ x } 10^6 \text{ x } 1.6 \text{ x } 10^{-19})}{(3 \text{ x } 10^8)^2}$
$\Delta m = 3.757 \text{ x } 10^{-28}$ kg
$m = \frac{\Delta m}{2}$
$m = \frac{3.757 \text{ x } 10^{-28}}{2}$
$m = 1.88 \text{ x } 10^{-28}$ kg</td><td>

1
1

1
1</td></tr>
</table>