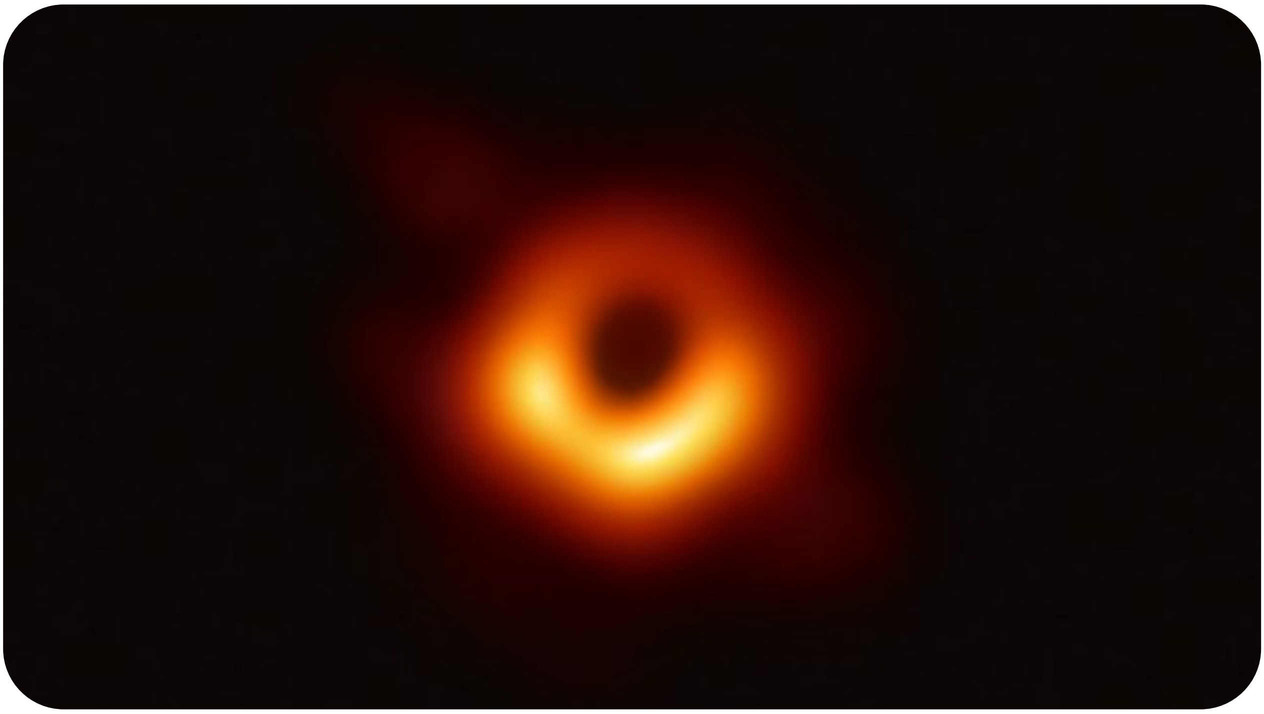
EDEXCEL International Advanced Level



# Edexcel IAL Physics Unit 4

*Summary©*

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HS

# Further Mechanics

## 1 Momentum

Momentum is a useful measure of motion, which is defined mathematically as the product of mass and velocity:

Momentum = mass x velocity

$$p = m \times v$$

Momentum is a vector quantity and always has both magnitude and direction.

**The momentum of an object is a measure of the accelerating force, applied over a period of time that is needed to bring the object from rest to the speed at which it is moving.** An object's momentum is also the force required, over a period of time, to bring the moving object to rest.

## 2 Newton's second law

Newton's law, F=ma only holds true if the mass remains constant. A more precise way in which this law is explained is:

**The rate of change of momentum of a body is directly proportional to the resultant force applied to the body, and is in the same direction as the force.**

This can be written mathematically as:

$$F = \frac{dp}{dt} = \frac{d(mv)}{dt}$$

The $\frac{d(x)}{dt}$ term is a mathematical expression meaning the rate of change of x, or how quickly x changes. If the quantities are not constantly changing, we can express this as:

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

The product of a force applied for a certain time is known as the impulse.

$$impulse = F \times \Delta t = \Delta p$$

To stop something moving, we need to remove all of its momentum. This idea allows us to calculate the impulse needed to stop a moving object. And if we know for how long a force is applied, we can work out the size of that force which ought to be negative as it is in the reverse direction.

# 3 NEWTON'S THIRD LAW

Conservation of momentum is directly responsible for this law. It tells us that for every force, there is an equal and opposite force. If we think of a force as a means to change momentum, then a force changing momentum in one direction must be countered by an equal and opposite force to ensure that overall momentum is conserved.

# 4 COLLISIONS

## Conservation of linear momentum

**The total momentum of a system remains constant provided that no external forces act on the system.** This applies to all objects moving in a straight line. This tells us that if we calculate the momentum of each body before the collision, the sum total of these momenta accounting for their direction will be the same as the sum total afterwards.

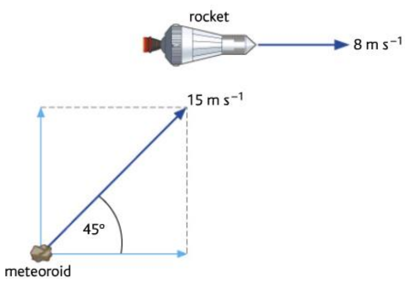
This principle is dependent on the condition that no external force acts on the objects in question. An external force would provide an additional acceleration, so the motion of the objects would not be dependent on the collision alone.

## Explosions

**If a stationary object explodes, then the total momentum of all the shrapnel parts added up must be zero.** The object had zero momentum at the start, so the principle of conservation of linear momentum tells us this must be the same total after the explosion.

## Conservation of linear momentum in 2D

When the objects are moving along different lines, we can resolve the velocity vectors into perpendicular directions and carry out the momenta sums for the component directions.




**Before**

Parallel to rocket motion:

$v_{meteoroid} = 15\cos 45° = 10.6\,\mathrm{m\,s^{-1}}$

$p_{meteoroid} = 20 \times 10.6 = 210\,\mathrm{kg\,m\,s^{-1}}$

$p_{rocket} = 350 \times 8.0 = 2800\,\mathrm{kg\,m\,s^{-1}}$

$p_{parallel} = 2800 + 210 = 3010\,\mathrm{kg\,m\,s^{-1}}$

Perpendicular to rocket motion:

$v_{meteoroid} = 15\sin 45° = 10.6\,\mathrm{m\,s^{-1}}$

$p_{meteoroid} = 20 \times 10.6 = 210\,\mathrm{kg\,m\,s^{-1}}$

$p_{rocket} = 350 \times 0 = 0$

$p_{perpendicular} = 0 + 210 = 210\,\mathrm{kg\,m\,s^{-1}}$

**After**

Vector sum of momenta (**fig. 1.1.11**):

$p_{total} = \sqrt{3010^2 + 210^2} = 3020\,\mathrm{kg\,m\,s^{-1}}$

$$v_{after} = \frac{p_{total}}{(m_{rocket} + m_{meteoroid})} = \frac{3020}{(350 + 20)} = 8.2\,\mathrm{m\,s^{-1}}$$

Angle of momentum (i.e. direction of velocity) after collision:

$$\theta = \tan^{-1}\left(\frac{210}{3010}\right) = 4.0°$$

So, the rocket with embedded meteoroid carries on at $8.2\,\mathrm{m\,s^{-1}}$ at an angle of 4.0° to the original direction of motion.

# 5 ENERGY IN COLLISIONS

## Elastic collisions

A collision in which kinetic energy is conserved is called an elastic collision. In life, these are rare. A collision caused by non-contact forces, such as alpha particles being scattered by a nucleus is perfectly elastic.

## Inelastic collisions

A collision in which kinetic energy is not conserved is called an inelastic collision. Some of the kinetic energy is converted into other forms such as heat and sound.

# 6 PARTICLE COLLISIONS

We know that the formula for calculating kinetic energy is $E_k = \frac{1}{2}mv^2$ and that the formula for momentum is $p = mv$. By combining these relationships we can get an equation that gives kinetic energy in terms of the momentum and mass.

$$E_k = \tfrac{1}{2} mv^2 \qquad \text{and} \qquad v = \frac{p}{m}$$

$$\therefore E_k = \tfrac{1}{2} m\left(\frac{p}{m}\right)^2$$

$$E_k = \tfrac{1}{2} \frac{p^2}{m}$$

$$E_k = \frac{p^2}{2m}$$

This is a particularly useful formula when dealing with the kinetic energy of subatomic particles travelling at non-relativistic speeds.

This formula offers an alternative way of calculating the de Broglie wavelength for a particle if we know its energy and mass:

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

$$\lambda = \frac{h}{\sqrt{2E_k m}}$$

# 7 CIRCULAR MOTION

## Angular displacement

When we are measuring rotation, we often use an alternative measure of angle called the radian. The angle, through which the object moves, measured in radians, is defined as the distance it has travelled along the circumference divided by its distance from the centre of circle.

$$\theta = \frac{s}{r}$$

- $\pi\ radians$ = 180°

Angular displacement is the vector measurement of the angle through which something has turned. The standard convention is that anticlockwise rotation is a positive number and clockwise rotation is a negative number.

## Angular velocity

The rate which the angular displacement changes, is called the angular velocity, w. so, constant angular velocity is defined mathematically by:

$$\omega = \frac{\theta}{t}$$

If the object completes a full circle in a time period T, then the angular is given by:

$$\omega = \frac{2\pi}{T}$$

The frequency of rotation is the reciprocal of the time period:

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

So:

$$\omega = 2\pi f$$

## Instantaneous velocity

We know that $v = \frac{s}{t}$ and from the definition of the angle in radians $\theta = \frac{s}{r}$, so that $s = r\theta$. Thus:

$$v = \frac{r\theta}{t}$$

$$v = r\omega$$

# 8 CENTRIPETAL FORCE

As an object such as a hammer is whirled at a constant speed, the magnitude of the velocity is always the same. However, the direction the velocity is constantly changing and a change in velocity is an acceleration. Newton's first law tells us that acceleration will only happen if there is a resultant force. The hammer is constantly being pulled towards the centre of the circle. **For any object moving in a circle, there must be a force to cause this acceleration toward the centre of the circle – this is called the centripetal force.** If a force causes something to move in a circle, we identify it as the centripetal force for that circling object.

The resultant centripetal force needed will be larger if:

- The rotating object has more mass
- The object rotates faster
- The object is closer to the centre of the circle

## Centripetal force and acceleration

The mathematical formula for the centripetal force on an object moving in a circle is:

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

Using the relationship, $v = r\omega$, we can derive an alternative for centripetal force in terms of angular velocity:

$$F = \frac{mv^2}{r} = \frac{m(r\omega)^2}{r}$$

$$F = mr\omega^2$$

Since Newton's second law states that the resultant force is related to the acceleration it causes by the equation, $F = ma$, we can find the centripetal acceleration very easily:

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

$$a = \frac{v^2}{r}$$

Again using, $v = r\omega$, the centripetal acceleration can be expressed in terms of the angular velocity as:

$$a = r\omega^2$$

# Electric and magnetic fields

## 1 Electric fields

**Electric field is a region in space in which a charged object experiences a force.**

To visualize the forces caused by the field, we draw electric field lines which **show the direction in which a positively charged particle will be pushed by the force the field produces**. Like all field patterns **the closer the lines are together, the stronger the field is**.

The force that a charged particle will feel is the electric field strength (E) multiplied by the amount of charge on the particle in coulombs (Q), as given by the equation:

$$F = EQ$$

From this force equation, we can also quickly calculate how a charge would accelerate. Newton`s second law states that $F = ma$, so we can equate the equations for force:

$$F = EQ \ = ma$$

So:

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

Electric field strength E is a vector quantity. The direction of E is the same as the direction of the electric force F, which is defined as the force on a positive charge.

## 2 Potential difference and electric fields

For a charged particle moving in an electric field, the change in its kinetic energy is provided in a transfer from the electric potential energy the electron had by virtue of its location within the electric field. **Every location within a field has a certain potential. The different between the potential at an electron`s original location and the potential at a new location is the potential difference through which the electron moves.**

Potential difference is defined as the energy transferred per coulomb of charge passing through the device. In an electric field, we can follow exactly the same idea in order to find out how much kinetic energy a charged particle will gain by moving within the field. This is given by the equation:

$$E = VQ$$

# 3 UNIFORM ELECTRIC FIELDS

**An electric field exists between any objects which are at a different electric potential.** Two oppositely charged plates placed parallel to each other produce a uniform electric field between. In a uniform electric field, the electric lines of force are equally spaced. When you move a small charged object around in a uniform electric field, the force on it remains constant. Because $E = \frac{F}{Q}$, this means that the value of E is the same everywhere.

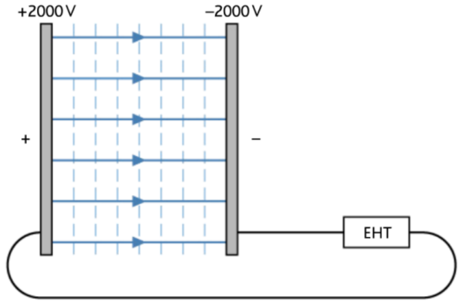



fig. 2.1.2 The blue arrows show the direction of the uniform electric field produced between parallel plates which have a potential difference between them.

**The strength of a uniform electric field is a measure of how rapidly the potential changes.** The equation which describes this divides the potential difference by the distance over which the potential difference exists:

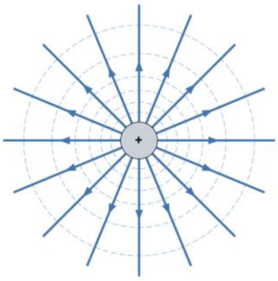
$$E = \frac{V}{d}$$

Where V is the potential difference between the oppositely charged parallel plates or surfaces producing the electric field and d is the separation of the surfaces.

## Equipotentials

As we move through an electric field, the electrical potential changes from place to place. Those locations which all have the same potential can be connected by lines called equipotential. The field will always be perpendicular to the equipotential lines, as **a field is defined as a region which changes the potential**. Remember that field lines never cross each other.

# 4 RADIAL FIELDS



In the region around a positively charged sphere, or a point charge like a proton, the electric field will act outwards in all directions away from the centre of the sphere. The arrows in the diagram get further apart as you move further away from the sphere, indicating that the field strength reduces as you move away from the centre. This means that the distance between equipotentials also increases. The field is the means by which the potential changes, so if it is weaker, then the potential changes less quickly.

# 5 COMBINATION ELECTRIC FIELDS

In a region where there are electric fields caused by more than one charged object, the **overall field is the vector sum at each point of the contributions from each field**.

Charge is particularly concentrated in regions around spikes or points on charged objects. The field lines are close together at these places and the field will be strong around them. HSW – This is why lightning conductors are spiked. The concentrated charge at the point will attract the lightning more strongly.

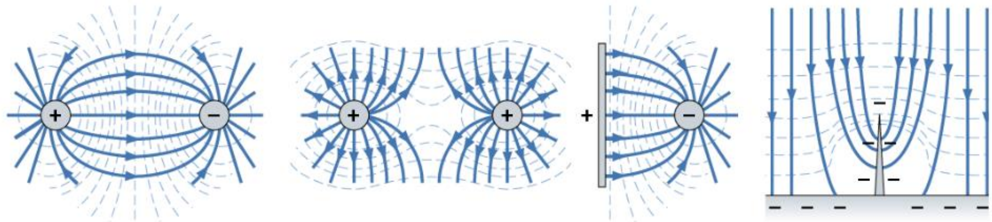


fig. 2.1.6 Complex fields still have their equipotentials perpendicular to the field lines at all points.

# 6 CHARGE PARTICLE INTERACTIONS – COULOMB'S LAW

The attraction between a proton and an electron can be imagined as the proton creating an electric field because of its positive charge, and the electron feeling a force produced by the proton's field.

The basic law describing the size of the force F between two point charges $Q_1$ and $Q_2$, which are separated by a distance r, is described by Coulomb's law and is given by the inverse-square law relationship:

$$F = \frac{kQ_1Q_2}{r^2}$$

Where $k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9$ N m$^2$ C$^{-2}$. Here $\varepsilon_0$ is a constant known as the permittivity of space, which is a measure of how easy it is for an electric field to pass through space.

## Radial field calculations

We have seen that an electric field can be defined as a region of space which will produce a force on a charged particle. This definition allows us to come up with an expression for the strength of a radial electric field using the expressions for force on a charged particle met earlier:

$$F_{coulomb} = E_1 Q_2 = \frac{kQ_1Q_2}{r^2}$$

Thus, the radial field strength at a distance r from a charge Q is given by:

$$E = \frac{kQ_1}{r^2}$$

## HSW – Powers of ten

| Factor | Name | Symbol | Factor | Name | Symbol |
|---|---|---|---|---|---|
| $10^{24}$ | yotta | Y | $10^{-1}$ | deci | d |
| $10^{21}$ | zetta | Z | $10^{-2}$ | centi | c |
| $10^{18}$ | exa | E | $10^{-3}$ | milli | m |
| $10^{15}$ | peta | P | $10^{-6}$ | micro | μ |
| $10^{12}$ | tera | T | $10^{-9}$ | nano | n |
| $10^{9}$ | giga | G | $10^{-12}$ | pico | p |
| $10^{6}$ | mega | M | $10^{-15}$ | femto | f |
| $10^{3}$ | kilo | k | $10^{-18}$ | atto | a |
| $10^{2}$ | hecto | h | $10^{-21}$ | zepto | z |
| $10^{1}$ | deka | da | $10^{-24}$ | yocto | y |

## HSW – Comparing gravitational and electric fields

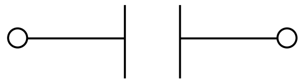
| | Gravitational effects | Electrostatic effects |
|---|---|---|
| Field strength | $g = \frac{F_g}{m}$<br>unit $N kg^{-1}$ or $m s^{-2}$ | $E = \frac{F_e}{Q}$<br>unit $N C^{-1}$ or $V m^{-1}$ |
| Potential difference in a uniform field | $g\Delta h$, that is $\frac{\Delta(GPE)}{m}$<br>unit $J kg^{-1}$ (no name) | $E\Delta x$, that is $\frac{\Delta(EPE)}{Q}$<br>unit $J C^{-1}$ or V |
| Energy conservation in a uniform field | $\Delta(\frac{1}{2}mv^2) = mg\Delta h$ | $\Delta(\frac{1}{2}mv^2) = Q\Delta V$ |
| Force laws | Newton: $F = \frac{Gm_1m_2}{r^2}$<br>$G = 6.67 \times 10^{-11}\ N m^2 kg^{-2}$ | Coulomb: $F = \frac{kQ_1Q_2}{r^2}$<br>$k$ or $\frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9\ N m^2 C^{-2}$ |
| Radial fields | $g = \frac{Gm}{r^2}$ | $E = \frac{kQ}{r^2}$ or $\frac{Q}{4\pi\varepsilon_0 r^2}$ |
| Potential difference in a radial field | $-Gm\left(\frac{1}{r_2} - \frac{1}{r_1}\right)$ | $kQ\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$ |
| Potential in the Earth's gravitational field or a point electric charge | $V_{grav} = \frac{-Gm_E}{r}$ | $V = \frac{kQ}{r}$ or $\frac{Q}{4\pi\varepsilon_0 r}$ |
| Graphs | inverse square, $g \propto \frac{1}{r^2}$<br>so $gr^2$ is constant | inverse square, $E \propto \frac{1}{r^2}$<br>so $Er^2$ is constant |

There are, of course, differences between the two phenomena. One obvious one is that gravity is about masses but electricity is about charges. Other differences include:

- Gravitational forces affect all particles with mass, but electrostatic forces affect only particles that carry charge.
- Gravitational forces are always attractive but electrostatic forces can be either attractive or repulsive.
- It is not possible to shield a mass from a gravitational field but it is possible to shield a charge from an electrostatic field.

# 7 CAPACITANCE

Circuit symbol of a capacitor:



## Electric fields in circuits

An electric field can cause charged particles to move. Indeed, this is why a current flows through a circuit – an electric field is set up within the conducting material and this causes electrons to feel a force and thus move through the wires and components of the circuit. Where there is a gap in a circuit, although the effect of the electric field can be felt by charges across empty space, conduction electrons are generally unable to escape their conductor and move across a gap. This is why a complete path is needed for a simple electric circuit to function.

However, charge can be made to flow in an incomplete circuit. When the power supply is connected, the electric field created in the conducting wires, causes electrons flow towards the positive terminal. Since the electrons cannot cross the gap between the plates they build up on the plate connected to the negative terminal, which becomes negatively charged. Electrons in the plate connected to the positive terminal flow towards the positive terminal, resulting in a positive charge on that plate. The attraction between opposite charges across the gap creates an electric field between the plates, which increases until the pd across the plates is equal to the pd of the power supply.

A pair of plates like this with an insulator between them is called a capacitor. Charge will build up on a capacitor until the pd across the plates equals that provided by the power supply to which it is connected. At that stage it is said to be fully charged. The capacitor is acting as a store of charge. The amount of charge a capacitor can store, per volt applied across it, is called its capacitance, C, and is measured in farads (F). The capacitance depends on the size of the plates, their separation, and the nature of the insulator between them.

Capacitance can be calculated from the equation:

$$C = \frac{Q}{V}$$

## Energy stored on a charged capacitor

A charged capacitor is a store of electrical potential energy. When the capacitor is discharged, this energy can be transferred into other forms.

$$E = QV$$

However, the energy stored in a charged capacitor is given by:

$$E = \frac{1}{2}QV$$

- In order to charge a capacitor, it begins with zero charge stored on it and slowly fills up as the pd increases, until the charge at voltage V is given by Q. Each time extra charge is added, it has to be done by increasing the voltage and pushing the charge on, which requires energy. Work is done against the repulsion between like charges.

Q=CV, so we can use this to find two other versions of the equation for stored energy:

$$E = \frac{1}{2}QV$$

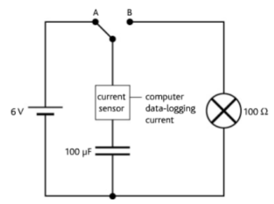
$$= E = \frac{1}{2}(CV)V$$

$$= E = \frac{1}{2}CV^2$$

Or

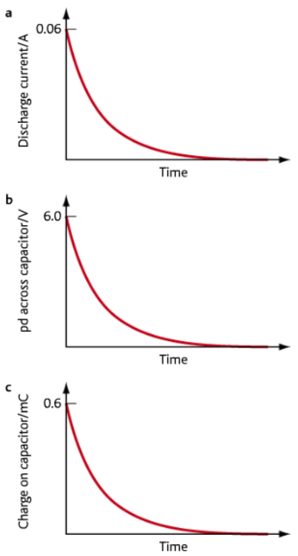
$$E = \frac{1}{2}Q\left(\frac{Q}{C}\right) = \frac{1}{2}\frac{Q^2}{C}$$

# 8 CAPACITOR DISCHARGE




If the two way-switch is moved to position B, the electrons on the capacitor will be able to move under the influence of the electric field towards the positive side of the capacitor. To do this they will flow through the lamp.

At first, the rush of electrons as the capacitor discharges is as high as it can be – the current starts at a maximum. As electrons flow from the discharging capacitor, the pd across it is reduced and the electric field and hence the push on the remaining electrons is weaker. The current is less. Eventually, the capacitor will be fully discharged and there will be no more electrons moving from one side of the capacitor to the other – the current will be zero. The discharging current, pd across the capacitor, and charge remaining on the capacitor will follow the patterns as shown below:




scharge curves for a capacitor discharging through a lamp.

Increasing the time of discharge:

There are two possibilities. For the same maximum pd, increasing the capacitance, C, will increase the charge stored, as Q = CV. Alternatively, the charge would flow more slowly if the resistance, R, in the lamp circuit was greater.

An overall impression of the rate of discharge of a capacitor can be gained by working out the time constant, $\tau = RC$, and with resistance in ohms and capacitance in farads, the answer is in seconds. In fact, the time constant tells you how many seconds it takes for the current to fall to 37% of its starting value.

By considering the charging process in the same way, it is possible to work out that the charging process produces similar graphs.

When charging through a resistor, the time constant RC has exactly the same implications. A greater resistance, or a larger capacitance, or both, means the circuit will take longer to charge up the capacitor.

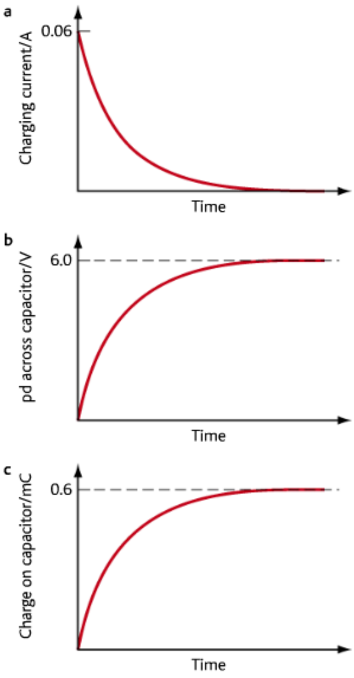



fig. 2.2.9 Charging curves for a capacitor connected to a 6V supply.

# 9 DISCHARGING CAPACITOR MATHS

The charging and discharging of a capacitor follows curved graphs in which the current is constantly changing, and so the rate of change of charge and pd are also constantly changing. These graphs are known as exponential curves. The shapes can be produced by plotting mathematical formulae which have power functions in them. In the case of discharging a capacitor, C, through a resistor, R, the function which describes the charge remaining on the capacitor, Q, at a time, t, is:

$$Q = Q_0 e^{-\frac{t}{RC}}$$

The pd across a discharging capacitor will fall as the charge stored falls. By substituting the equation Q = CV into our exponential decay equation, we can show that the formula that describes voltage on a discharging capacitor has exactly the same form as that for the charge itself:

$$Q = Q_0 e^{-\frac{t}{RC}} \text{ and Q = CV}$$

$$CV = CV_0 e^{-\frac{t}{RC}}$$

From which the capacitance term, C, can be cancelled, leaving:

$$V = V_0 e^{-\frac{t}{RC}}$$

The discharging current also dies away following an exponential curve. Ohm's law tells us that V = IR, and hence $V_0 = I_0 R$.

$$IR = I_0 R e^{-\frac{t}{RC}}$$

From which the resistance term, R will cancel on both sides:

$$I = I_0 e^{-\frac{t}{RC}}$$

# 10 MAGNETIC FIELDS

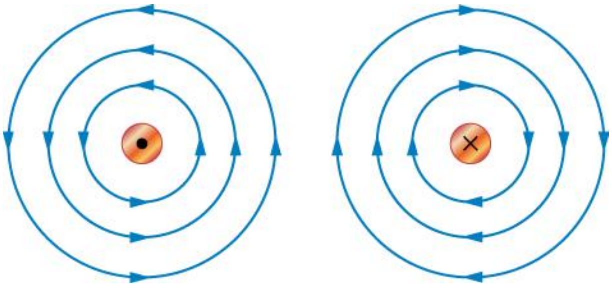
A magnetic field is a region in which magnetic materials or moving electrical charges experience a force.

- Magnetic lines are used just as electric lines to illustrate the direction and strength of magnetic fields.
- There is a simple convention for the N and S labels on the magnets and for the arrows on the lines of the force.
- Magnetic lines of force flow from N to S.
- N and S are called the poles of the magnet.
- Like electric fields, the magnetic field is strongest, that it exerts the largest forces, at places where the magnetic field lines are most closely bunched.
- Unlike positive and negative electric charges, an isolated N or S pole has never been found.

Electric and magnetic fields are in fact very similar as seen and utterly intertwined, as Maxwell's work on the nature of electromagnetic radiation taught us.

> Maxwell's theoretical research on electromagnetic radiation essentially unified moving electric and magnetic fields to explain how light moves and interacts with matter. His equations are quite complex but, for fixed fields, there are some quite simple outcomes which have important applications for us here:
>
> - an electric field can exert a force on a charged particle
> - a magnetic field can exert a force on a charged particle if it is moving.

Electric currents also produce magnetic fields. Magnetic lines of force in these magnetic fields are always closed loops. The field with the simplest shape is that produced by a steady current in a long straight wire.

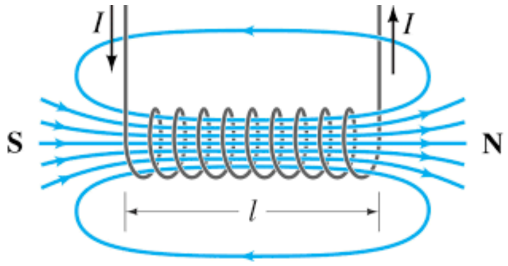


Current out of page

Current into page

The magnetic field lines are a series of concentric circles; the field is getting weaker further from the wire.

Magnetic field of current-carrying coil




# 11 MAGNETIC FIELD STRENGTH

When a current-carrying wire is placed at right angles to a uniform magnetic field, the magnetic fields interact, resulting in a force F on the wire. This force depends on the current I in the wire and the length l of the wire that lies in the field:

$$F \propto Il$$

The strength of the field, which is called the magnetic flux density B, is a vector quantity, and is defined as the constant of proportionality, so:

$$F = B_{\perp}Il$$

The suffix ⊥ indicates that the wire carrying the current must be perpendicular to the magnetic field. This equation can be written as:

$$F = BIlsin\theta$$

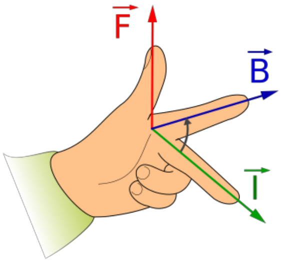
Where $B_{\perp} = Bsin\theta$ and $\theta$ is the angle between B and the wire.

The unit N $A^{-1}$ $m^{-1}$ emerges from the calculation. This unit is usually given the name tesla, symbol T.

A consequence of the expression $F = B_{\perp}Il$ is that a motor can be made more powerful, or faster by:

- Increasing the current through the motor
- Increasing the number of turns of wire in the motor
- Increasing the magnetic field within the motor

# 12 FLEMING'S LEFT HAND RULE




Like gravitational field strength, and electric field strength, magnetic field strength, B, is a vector quantity. But unlike gravitational and electric fields, where the forces are parallel to the fields, the magnetic force is perpendicular to both the field and the current-carrying wire. Left-hand rule is used to illustrate this in 3D.

Remember that the left hand rule applies to the sense of conventional current, or to the sense of motion of positive charge, and not to the direction of motion of negatively charged electrons, which will be in the opposite direction.

# 13 F = BQVSIN$\theta$

The current I in the wire is the result of the drift of very large numbers of electrons in the wire. The relationship linking the current to the drift speed of the charged particles is:

$$I = nAvq$$

Where n is the number of charge carriers per unit volume, A is the cross-sectional area of the wire, q is the charge on each charge carrier and v is the drift speed of the charge carriers.

As the force on a wire is given by $F = B_{\perp}Il$, inserting $I = nAvq$ gives $F = B_{\perp}(nAvq)l$, which can be rearranged as:

$$F = B_{\perp}vq \times nAl$$

In this equation Al is the volume of the wire in the magnetic field, so nAl is the total number N of charge carriers in that piece of wire.

Hence $\frac{F}{nAl}$ is equal to $\frac{F}{N}$, that is, it is the force on one of these charge carriers.

<u>The result is that the force F on one charged particle moving at speed v perpendicular to a magnetic field of flux density B is given by:</u>

$$F = B_{\perp}qv$$

Hence, $F = Bqvsin\theta$

As the force on a charged particle is always at right angles to the direction of its velocity, it acts as a centripetal force, and the particle follows a circular path. This means that, given the right combination of conditions, a moving charged particle could be held in place by a magnetic field, continuously orbiting a central point. This is the principle by which artificially generated antimatter is contained to save it from annihilation, for future use or study.

The force on a charged particle moving at right angles to a magnetic field is given by:

$$F = B_{\perp}qv$$

Centripetal force is given by:

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

Combining these gives:

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

# 14 ELECTROMAGNETIC INDUCTION

The movement of a charged particle in a magnetic field causes it to feel a force. Newton's third law of motion states that this force must have a counterpart which acts equally in the opposite direction. Moreover, this pair of electromagnetic forces is generated whenever there is relative motion between a charge and a magnetic field. Thus, a magnetic field moving past a stationary charge will create the same force. The velocity term in the expression $F = B_{\perp}qv$ actually refers to the relative perpendicular velocity between the magnetic field lines and q.

This means that if we move a magnet near a wire, the electrons in the wire will feel a force tending to make them move through the wire. This is an emf – if the wire is in a complete circuit, then the electrons will move, forming an electric current. This is one principle by which we generate electricity. Reversing the direction of the magnetic field, or the direction of the relative motion will reverse the direction of the force on the electrons, reversing the polarity of emf.

# 15 FLUX LINKAGE

The product of magnetic flux density and the area through which it acts is called the magnetic flux through the area, symbol $\Phi$.

$$\Phi = \mathrm{B}_{\perp}\mathrm{A}$$

However, for a coil with N number of turns this equation becomes:

$$\Phi = \mathrm{NB}_{\perp}\mathrm{A}$$

As $F = B_{\perp}qv$, it is no surprise that the faster the relative motion between a magnetic field and a conductor, the greater the induced emf. Faraday investigated this and determined a law on matter. Faraday's law of electromagnetic induction states that:

**The magnitude of an induced emf is proportional to the rate of change of flux linkage.**

# 16 LENZ'S LAW

**Lenz's law states that the induced emf must cause a current to flow in such a direction as to oppose the change in flux linkage that produces it**, otherwise energy would appear from nowhere.

# 17 CALCULATING INDUCED EMFS

Putting Faraday's and Lenz's laws together gives us an expression for calculating an induced emf:

$$\varepsilon = \frac{-d(N\Phi)}{dt}$$

Faraday's law told us that the emf would be proportional to the rate of change of flux linkage. The minus sign in the equation comes from Lenz's law, to indicate the opposing direction.

## HSW and RECALL from IGCSE

### DC motors

- As a current passes through a coil in a magnetic field, one side of it will experience and upward force while the other side experiences a downward force. So there is a turning moment in the coil. Commutator changes the direction of the current once in a half turn, so rotation is continuous.

<u>In practical motors:</u>

- The permanent magnets are replaced with electromagnets.
- Single loop is replaced with several coils of wire wrapped on the same axes.
- The coils are wrapped on a laminated iron core.

<u>To increase the rate of turning of motors:</u>

- Increase the current
- Increase the number of turns in coil
- Increase magnetic field

### Electromagnetic induction

When a wire is moved in a magnetic field, a voltage is induced. If the wire is a part of complete circuit, an induced current passes through it. This is called electromagnetic induction.

<u>To increase the size of induced voltage:</u>

- Move wires faster
- Increase the number of turns in coil
- Increase magnetic field
- Cross-sectional area of the coil can be increased.

### Faraday's law of electromagnetic induction

The size of the induced voltage across the ends of wire is directly proportional to the rate at which the magnetic lines of flux are being cut.

### Lenz's law

When a current is induced, it always opposes the change in magnetic field.

### To increase the size of induced current:

- Move magnet faster
- Increase the number of turns in the solenoid
- Use stronger magnet
- Use a thicker iron core

## Loudspeakers

- Motor effect is applied to loudspeakers.
- A coil is attached to a paper cone. The changing current in the coil produces a changing magnetic field which interacts with the field from the permanent magnet.
- This creates backwards and forwards motion of the coil and paper cone.
- This makes the air vibrate and sound waves are generated.

## Electric generator

➔ As the coil rotates, its wires cut through magnetic field lines and a current is induced in them. The current induced in the coil flows first in one direction and then in opposite direction. This kind of current is alternating current. It changes direction once every half turn.

### To increase the size of pd:

- Turning the coil faster
- Using stronger magnets
- Increasing the number of turns
- Using an iron core

## Transformers

A transformer changes the size of an alternating voltage by having different number of turns on the primary coil and secondary coil. Alternating current in the primary coil produces an alternating magnetic field. Iron core is magnetised and links the alternating magnetic field to the secondary coil. An alternating current is induced in the secondary coil.

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

Power input equals the power output in ideal transformers. Therefore,

$$V_p I_p = V_s I_s$$

# Particle physics

## 1 ALPHA PARTICLE SCATTERING

Geiger and Marsden undertook an experiment in which they aimed an alpha particle source at an extremely thin gold foil. Their expectation was that all the alpha particles would pass through, possibly with little deviation. The results generally followed this pattern – the vast majority passed straight through the foil. However, a few alpha particles had their trajectories deviated by quite large angles. Some were even repelled back the way they had come.

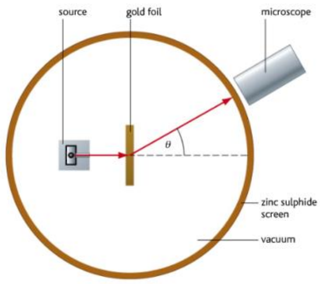


fig. 3.1.2 Rutherford's alpha particle scattering apparatus.

| Angle of deflection/degrees | Evidence | Conclusion |
|---|---|---|
| 0–10 | Most alpha particles pass straight through with little deviation. | Most of the atom is empty space. |
| 10–90 | Some alpha particles deflected through a large angle. | All the atom's positive charge is concentrated in one place. |
| 90–180 | A few alpha particles are repelled back towards the source side of the foil. | Most of the mass, and all positive charge, is in a tiny, central nucleus. |

table 3.1.1 Evidence and conclusions from Rutherford's alpha particle scattering experiment.

## 2 NUCLEAR STRUCTURE

The nucleus made up from two particles: the proton and the neutron. Collectively these two particles, when in a nucleus, are known as nucleons. The number of protons in a nucleus determines which element the atom will be. The periodic table is a list of the elements ordered according to the number of protons in each atom's nucleus. This number is called the proton number or the atomic number. For small nuclei, the number of neutrons in the nucleus is generally equal to the number of protons. Above atomic number 20, for the nucleus to be stable more neutrons than protons are generally needed. The neutrons help to bind the nucleus together as they exert a strong nuclear force on other nucleons, and they act as a space buffer between the mutually repelling positive charges of the protons.

## 3 ELECTRON BEAMS

Free conduction electrons in metals need a certain amount of energy if they are to escape from the surface of the metal structure. The electrons can gain enough energy through heating of the metal. The release of electrons from the surface of a metal as it is heated is known as thermionic emission.

If, on escaping, these electrons find themselves in an electric field, they will be accelerated by the field, moving in the positive direction. The kinetic energy they gain will depend on the pd, V, that they move through, according to the equation:

$$E_k = eV$$

Using thermionic emission to produce electrons, and applying an electric field to accelerate them, we can generate a beam of fast-moving electrons, traditionally known as cathode ray. This beam of electrons will be deflected by a magnetic field. If a fast-moving electron hits a screen painted with a certain chemical, the screen will fluoresce – it will emit light.

# 4 ELECTRONS AS WAVES

Electrons do not just behave as particles – they also have wave properties. De Broglie's wave equation relates the wavelength of a particle to its momentum:

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

The idea of electrons acting as waves has allowed scientists to study the structure of crystals. When waves pass through a gap which is about the same size as their wavelength, they are diffracted – they spread out. The degree of diffraction spreading depends on the ratio of the size of the gap to the wavelength of the wave. Electron diffraction and alpha particle scattering both highlight the idea that we can study the structure of matter by probing it with beams of high-energy particles. **The more detail – or smaller scale – the structure to be investigated, the higher energy the beam of particles needs to be.**

# 5 PARTICLE ACCELERATORS

To investigate the internal substructure of particles, scientists collide them with other particles at very high speeds (very high energies). If we can collide particles together hard enough they will break up, revealing their structure. In most cases additional particles are created from the energy of the collision.

The challenge for scientists has been to accelerate particles to sufficient speeds. Charged particles can be accelerated in straight lines using a potential difference, and their direction changed along a curved path by a magnetic field.

## Linear accelerators

A linear accelerator operates on the same principle as an electron gun – electrons or other charged particles are accelerated across gaps between charged electrodes. In a linac, there often many drift tubes connected to a high-frequency, high-voltage AC supply. These are arranged in such a way that the particles gain kinetic energy between the tubes and move at constant speed inside the tubes. The main principles are:

- Alternate tubes are connected to each terminal of the AC supply.
- The charged particles spend one half of each period of the alternating voltage between two tubes and the other half of each cycle inside one of the tubes.

- During a half-cycle when the voltage would oppose their motion, the particles are inside a tube, where they are shielded from the electric field; the particles therefore travel at **constant speed within the tube**.
- The particles **gain kinetic energy** as they travel across successive gaps, and can be accelerated to high energies.
- The **length of the drift tubes increases** along the accelerator so that although the speed of the particles is increasing, the time needed to pass through each tube will always be the same (equal to the half period of the alternating electric field).

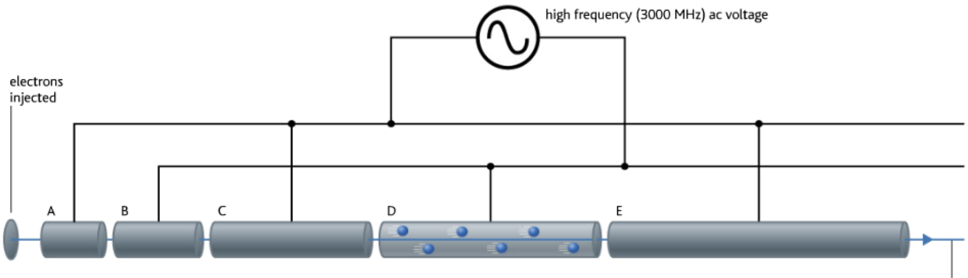


fig. 3.2.2 The structure of a linear accelerator.

# Cyclotron

The main disadvantage of linear accelerators is that, in order to produce high energies, they need to be very long. Cyclotrons, while based on the same principle of synchronous acceleration as linacs, use a magnetic field to make the charged particles move in a spiral path.

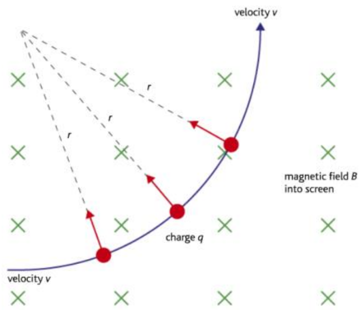


fig. 3.2.4 The circular trajectory of a charged particle moving across a magnetic field. Note that field lines can be shown coming out of a page by drawing a dot, and those going into a page (like the magnetic field here) can be shown by drawing a cross.

## Accelerating particles in circles

By Fleming's left-hand rule, a particle carrying a charge q moving with speed v at right angles to a magnetic field of flux density B will experience a force of magnitude Bqv in a direction perpendicular to its motion. The particle will therefore follow a circular path, and we have:

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

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

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

The main principles of a cyclotron are:

A cyclotron consists of two hollow, semicircular D-shaped sections which are placed at right angles to a uniform magnetic field and have a high-frequency alternating voltage applied between them.

- An ion source fires charged particles into the gap between the dees close to the centre.

- The particles are accelerated across the gap during a half-cycle of the alternating voltage when the polarity is appropriate.
- During the next half-cycle, the particles follow a circular path at constant speed in one of the dees.
- The particles are then accelerated across the gap into the other dee.
- **Faster particles follow paths of greater radius**, so that all particles spend the same amount of time in the dees and their acceleration is synchronised with the appropriate half-cycle of alternating voltage.

### Relativistic effects

For speeds approaching the speed of light, relativistic effects need to be taken into account. It is a basic postulate of the theory of relativity that nothing can travel beyond the speed of light. Therefore, for energy to be conserved, the **mass of the electron must increase**. Relativistic effects can therefore create synchronisation problems in high-energy particle accelerators. Synchrotrons, such as CERN, account for these relativistic effects and can produce particles with extremely high energy.

# 6 Particle detectors

Particles can be detected when they interact with matter to cause ionisation or when they excite electrons to higher energy levels, accompanied by the emission of photons.

In bubble tanks and cloud chambers, a charged particle passing through will generate a trail of ions along which bubbles or vapour droplets are formed, making these paths visible. The nature of the particles can be deduced from the length of trails they leave, and from how these paths are affected by electric and magnetic fields.

### Interpreting images

- Neutral particles do not produce a trail and cannot be observed.
- **Oppositely charged particles are deviated in opposite directions**, which is determined by Fleming's left-hand rule.
- From the relation $r = p / Bq$, we can infer that particles with **greater momentum spiral less**, so trails with greater radius indicate massive and/or energetic particles.
- A thicker trail indicates more intense ionisation, which is usually due to the particle having greater momentum or charge.
- Particles **spiral inwards**. This is because, as they lose energy, their momentum decreases and the radius of the path become smaller.

# 7 Particle interactions

In any interaction:

- Momentum is conserved.
- Mass/energy is conserved.

- Charge is conserved.
- Baryon number is conserved.
- Lepton number is conserved.
- Strangeness is conserved.

### Conservation of mass-energy

The rest mass of particles can be represented as an equivalent energy by means of Einstein's equation:

$$E_0 = m_0c^2 \text{ or } m_o = \frac{E_0}{c^2}$$

The rest mass can be thought of as the energy that would be transferred if the entire mass were to be dematerialised, or if the particle were to be made up completely from other forms of energy.

Remember mass of particles moving close the speed of light are greater than their rest mass. This is because nothing can travel beyond the speed of light, thus for momentum to be conserved mass must increase.

The mass of moving particles can be taken as being the same as their rest mass unless the sped is close to the speed of light.

### Units of mass and energy

It is often convenient to represent the rest mass of subatomic particles in terms of the non-SI units $MeV/c^2$ or $GeV/c^2$.

MeV and GeV are units of energy; $MeV/c^2$ and $GeV/c^2$ are the corresponding units of mass.

Another unit used in particle physics is the unified atomic mass unit, denoted by u. It is defined as one-twelfth of the mass of a carbon-12 atom, so

$$1u = 1.66 \times 10^{-27}kg$$

# 8 CREATION AND ANNIHILATION OF MATTER AND ANTIMATTER

Early work with particle detectors showed that cosmic rays could produce some tracks identical to those of an electron, but which curve in the opposite direction. This was the first piece of evidence for the existence of antimatter. Energy of photons was creating particles in a process known as pair production. This is called creation. Conversely, if a particle and antiparticle meet, they will spontaneously vanish from existence to be replaced by the equivalent energy. This is called annihilation. Einstein's famous equation is used to calculate the energy or mass created as a result of these processes.

$$\Delta E = c^2 \Delta m$$

In order to create a new particle the energy converted must be at least equal to the rest mass energy of the particle. If there is more energy converted, the new particle will gain some kinetic energy.

# 9 THE STANDARD MODEL

Our current ideas about fundamental particles are summarised by the standard model of particle theory. In this model there are two types of fundamental particle – quarks and leptons.

1-) Quarks are strongly interacting particles, and it is believed they do not exist singly. They occur in two possible combinations.

- In quark – anti-quark pairs, called mesons
- In quark triplets, called baryons.

Collectively mesons and baryons are referred to as hadrons. The proton and the neutron are familiar examples of baryons.

2-) Leptons are weakly interacting particles. Leptons occur singly; the electron to a familiar example of a lepton.

In the standard model there are six quarks and six leptons, plus their antiparticle equivalents.

| Generation | Name | Symbol | Charge | Mass (MeV/$c^2$) |
|---|---|---|---|---|
| I | Electron | $e^-$ | −1 | 0.511 |
| I | Electron neutrino | $\nu_e$ | 0 | 0 (<$2.2 \times 10^{-6}$) |
| II | Muon | $\mu$ | −1 | 106 |
| II | Muon neutrino | $\nu_\mu$ | 0 | 0 (<0.17) |
| III | Tau | $\tau$ | −1 | 1780 |
| III | Tau neutrino | $\nu_\tau$ | 0 | 0 (<20) |

| Generation | Name | Symbol | Charge | Mass (GeV/$c^2$) |
|---|---|---|---|---|
| I | Up | u | +2/3 | 0.003 |
| I | Down | d | −1/3 | 0.006 |
| II | Strange | s | −1/3 | 0.1 |
| II | Charm | c | +2/3 | 1.3 |
| III | Bottom | b | −1/3 | 4.3 |
| III | Top | t | +2/3 | 175 |

table 3.3.2 The family of quarks. These are subject to the strong nuclear force.

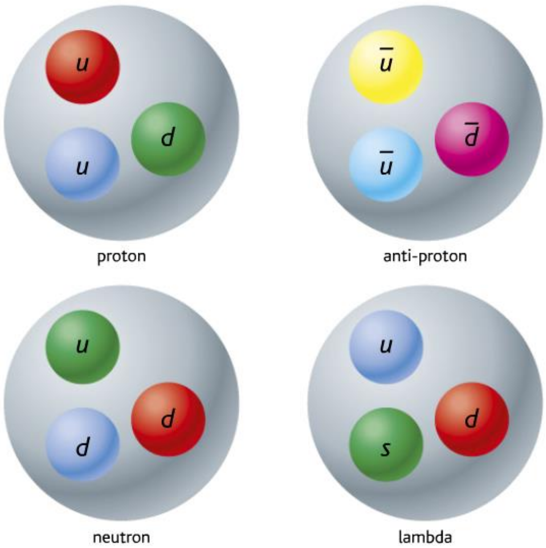



fig. 3.3.5 Three-quark baryons. Three anti-quarks in the anti-proton make it an **anti-baryon**.

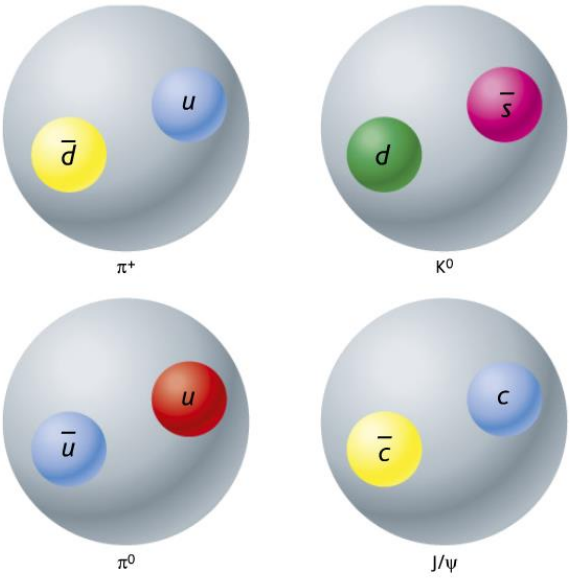



fig. 3.3.6 Mesons are formed from quark/anti-quark combinations.

# 10 WAVE-PARTICLE DUALITY - AGAIN

Diffraction patterns can be observed when high-energy electrons from an electron gun are fired through a thin slice of carbon, indicating that the electron, as well as being a particle, behaves like a wave. It is also possible to measure the radiation pressure of light from the Sun, which shows that photons have momentum, an attribute to all particles. This wave-particle duality applies to all particles, but it is significant only on a subatomic scale. The relationship between momentum p of a particle and its wavelength $\lambda$ is expressed by de Broglie's wave equation:

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

where h is the Planck constant.

In the electron diffraction experiment it was also observed that when the voltage across the electron gun is increased, the **higher-energy electrons produced have a shorter wavelength**. This relationship can be seen from Planck's photon equation.

$$E = \frac{hc}{\lambda}$$

The wavelength of a 100 keV electron is of the same order of magnitude as the diameter of a carbon atom, so a noticeable diffraction pattern is produced when an electron beam is focused on a specimen containing carbon. This principle is applied to electron microscopes.

If a high-energy accelerator is used, the wavelength of the electrons will be much shorter, and this enables the structures of hadrons to be probed using deep inelastic scattering.