

Particles and Waves



Summary Notes Part 1

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The Standard Model

Orders of Magnitude

Physics is the most universal of all sciences. It ranges from the study of particle physics at the tiniest scales of around 10^{-18} m to the study of the universe itself at a scale of 10^{29} m.

Often, to help us grasp a sense of scale, newspapers compare things to everyday objects: heights are measured in double decker buses, areas in football pitches etc. However, we do not experience the extremes of scale in everyday life so we use scientific notation to describe these. Powers of 10 are referred to as orders of magnitude, i.e. something a thousand times larger is three orders of magnitude bigger. The table below gives examples of distances covering 7 orders of magnitude from 1 metre to 10 million metres (10^7 m).

1 m	Human scale – the average British person is 1.69 m
10 m	The height of a house
100 m	The width of a city square
10^3 m	The length of an average street
10^4 m	The diameter of a small city like Perth
10^5 m	Approximate distance between Aberdeen and Dundee
10^6 m	Length of Great Britain
10^7 m	Diameter of Earth

As big as this jump is, you would need to repeat this expansion nearly four times more to get to the edge of the universe (at around 10^{28} m) Similarly we would need to make this jump more than twice in a smaller direction to get to the smallest particles we have discovered so far.

These scales are shown in the table on the following page.

Size	Powers of 10	Examples
	10^{-18} m	Size of an electron/quark?
1 fm (femto)	10^{-15} m	Size of a proton
	10^{-14} m	Atomic nucleus
1 pm (pico)	10^{-12} m	
1Å (Angstrom)	10^{-10} m	Atom
1 nm (nano)	10^{-9} m	Glucose molecule
	10^{-8} m	Size of DNA
	10^{-7} m	Wavelength of visible light. Size of a virus.
1 µm (micro)	10^{-6} m	Diameter of cell mitochondria
	10^{-5} m	Red blood cell
	10^{-4} m	Width of a human hair. Grain of salt
1 mm (milli)	10^{-3} m	Width of a credit card
1 cm (centi)	10^{-2} m	Diameter of a pencil. Width of a pinkie finger!
	10^{-1} m	Diameter of a DVD
1 m	10^0 m	Height of door handle
	10^1 m	Width of a classroom
	10^2 m	Length of a football pitch
1 km (kilo)	10^3 m	Central span of the Forth Road Bridge
	10^4 m	10km race distance. Cruising altitude of an aeroplane
	10^5 m	Height of the atmosphere
1 Mm (mega)	10^6 m	Length of Great Britain
	10^7 m	Diameter of Earth Coastline of Great Britain
1 Gm (giga)	10^9 m	Moon's orbit around the Earth, The farthest any person has travelled. The diameter of the Sun.
	10^{11} m	Orbit of Venus around the Sun
1 Tm (tera)	10^{12} m	Orbit of Jupiter around the Sun
	10^{13} m	The heliosphere, edge of our solar system?
	10^{16} m	Light year. Distance to nearest star Proxima Centauri,
	10^{21} m	Diameter of our galaxy
	10^{23} m	Distance to the Andromeda galaxy
	10^{29} m	Distance to the edge of the observable universe

The Standard Model of Particle Physics

The following pages introduce the background to the Standard Model of particle physics. It is important to realise that our current model of physics is constantly changing and being updated and improved as new experimental evidence is found.

What is the world made of?

The ancient Greeks believed the world was made of 4 **elements** (fire, air, earth and water). Democritus used the term 'atom', which means "indivisible" (cannot be divided) to describe the basic building blocks of life. Other cultures including the Chinese and the Indians had similar concepts.

Elements: the simplest chemicals

In 1789 the French chemist Lavoisier discovered through very precise measurement that the total mass in a chemical reaction stays the same. He defined an element as a material that could not be broken down further by chemical means, and classified many new elements and compounds.

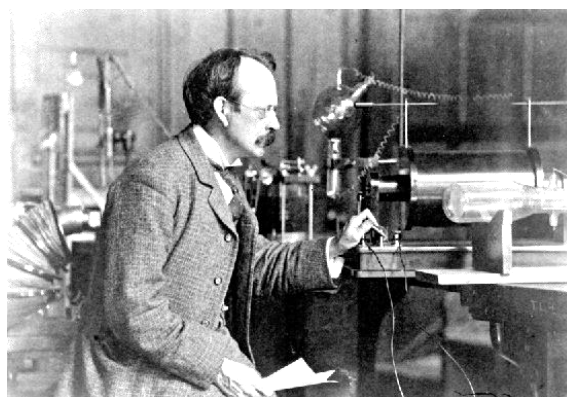


The periodic table – order out of chaos

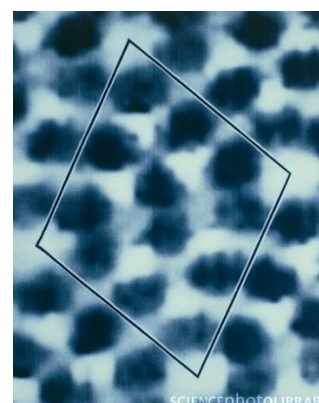
In 1803 Dalton measured very precisely the proportion of elements in various materials and reactions. He discovered that they always occurred in small integer multiples. This is considered the start of modern atomic theory. In 1869 Mendeleev noticed that certain properties of chemical elements repeat themselves periodically and he organised them into the first periodic table.

The discovery of the electron

In 1897 J.J. Thomson discovered the electron and the concept of the atom as a single unit ended. This marked the birth of particle physics. Photograph courtesy of the Cavendish Laboratory, Cambridge.



Although we cannot see atoms using light which has too large a wavelength, we can by using an electron microscope. This fires a beam of electrons at the target and measures how they interact. By measuring the reflections and shadows, an image of individual atoms can be formed. We cannot actually see an atom using light, but we can create an image of one. The image shows a false-colour scanning tunnelling image of silicon. © IBM/Science Photo Library



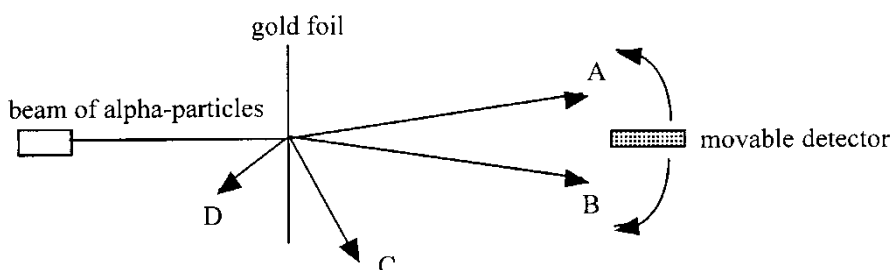
The structure of atoms

At the start of modern physics at the beginning of the 20th century, atoms were treated as semi-solid spheres with charge spread throughout them. This was called the Thomson model after the physicist who discovered the electron. This model fitted in well with experiments that had been done by then, but a new experiment by Ernest Rutherford in 1909 would soon change this. This was the first scattering experiment – an experiment to probe the structure of objects smaller than we can actually see by firing something at them and seeing how they deflect or reflect.



The Rutherford alpha scattering experiment

Rutherford directed his students Hans Geiger and Ernest Marsden to fire alpha particles at a thin gold foil. This is done in a vacuum to avoid the alpha particles being absorbed by the air.

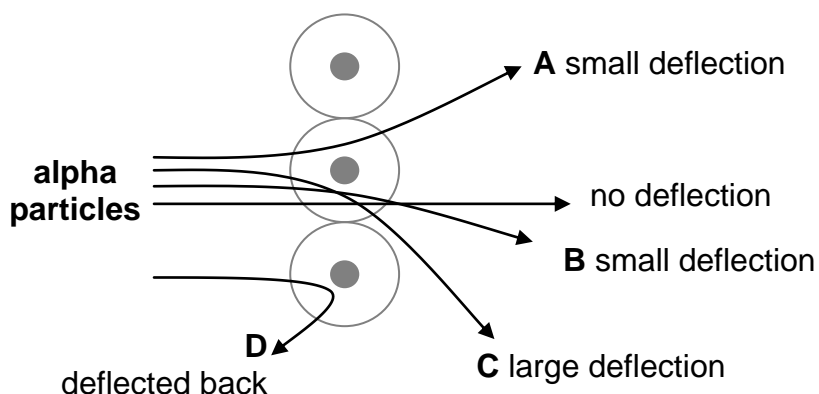


The main results of this experiment were:

- Most of the alpha particles passed straight through the foil, with little or no deflection, being detected between positions A and B.
- A few particles were deflected through large angles, e.g. to position C, and a very small number were even deflected backwards, e.g. to position D.

Rutherford interpreted his results as follows:

- The fact that most of the particles passed straight through the foil, which was at least 100 atoms thick, suggested that the atom must be mostly empty space!
- In order to produce the large deflections at C and D, the positively charged alpha particles must be encountering something of very large mass and a positive charge.



The discovery of the neutron

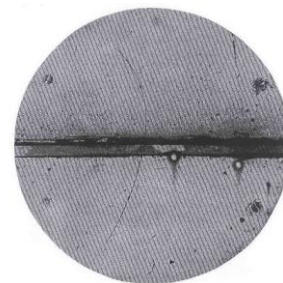
Physicists realised that there must be another particle in the nucleus to stop the positive protons exploding apart. This is the **neutron** which was discovered by Chadwick in 1932. This explained **isotopes** – elements with the same number of protons but different numbers of neutrons.

Science now had an elegant theory which explained the numerous elements using only three particles: the proton; neutron and electron. However this simplicity did not last long.

Matter and antimatter

In 1928, Paul Dirac found two solutions to the equations he was developing to describe electron interactions. The second solution was identical in every way apart from its charge, which was positive rather than negative. This was named the positron, and experimental proof of its existence came just four years later in 1932. (The positron is the only antiparticle with a special name – it means ‘positive electron’.)

The experimental proof for the positron came in the form of tracks left in a cloud chamber. The rather faint photograph on the right shows the first positron ever identified. The tracks of positrons were identical to those made by electrons but curved in the opposite direction. (You will learn more about cloud chambers and other particle detectors later in this unit.)



Almost everything we see in the universe appears to be made up of just ordinary protons, neutrons and electrons. However high-energy collisions revealed the existence of antimatter. **Antimatter consists of particles that are identical to their counterparts in every way apart from charge**, e.g. an antiproton has the same mass as a proton but a negative charge. It is believed that every particle of matter has a corresponding antiparticle.

Annihilation

When a matter particle meets an anti-matter particle they **annihilate**, giving off energy. Often a pair of high energy photons (gamma rays) are produced but other particles can be created from the conversion of energy into mass (using $E = mc^2$). Anti-matter has featured in science fiction books and films such as *Angels and Demons*. It is also the way in which hospital PET (Positron Emission Tomography) scanners work.

The particle zoo

The discovery of anti-matter was only the beginning. From the 1930s onwards the technology of particle accelerators greatly improved and nearly 200 more particles have been discovered. Colloquially this was known as the particle zoo, with more and more new species being discovered each year. A new theory was needed to explain and try to simplify what was going on. This theory is called the **Standard Model**.

The Standard Model

The standard model represents our best understanding of the fundamental nature of matter. It proposes 12 fundamental matter particles, fermions, organised in three generations. The first generation includes the electron, the neutrino and the two quarks that make up protons and neutrons, i.e. the normal matter of our universe. The other generations are only found in high-energy collisions in particle accelerators or in naturally occurring cosmic rays. Each has a charge of a fraction of the charge on an electron (1.60×10^{-19} C).

	First generation	Second generation	Third generation
Quarks	up ($\frac{2}{3}$)	charm ($\frac{2}{3}$)	top ($\frac{2}{3}$)
	down ($-\frac{1}{3}$)	strange ($-\frac{1}{3}$)	bottom ($-\frac{1}{3}$)
Leptons	electron (-1)	muon (-1)	tau (-1)
	(electron) neutrino (0)	muon neutrino (0)	tau neutrino (0)

These particles also have other properties, such as spin, colour, quantum number and strangeness, which are not covered by this course.

Leptons

The term 'lepton' (light particle - from the Greek, leptos) was proposed in 1948 to describe particles with similarities to electrons and neutrinos. It was later found that some of the second and third generation leptons were significantly heavier, some even heavier than protons.

Quarks

In 1964 Murray Gell-Mann proposed that protons and neutrons consisted of three smaller particles which he called 'quarks' (named after a word in James Joyce's book *Finnegans Wake*). Quarks have never been observed on their own, only in groups of two or three, called 'hadrons'.

Hadrons

Particles which are made up of quarks are called **hadrons** (heavy particle – from the Greek, hadros).

There are two different types of hadron, called **baryons** and **mesons** which depend on how many quarks make up the particle.

Baryons are made up of **3** quarks. Examples include the **proton** and the **neutron**.

The charge of the proton (and the neutral charge of the neutron) arise out of the fractional charges of their inner quarks. This is worked out as follows:

A **proton** consists of **2 up quarks and a down quark**. Total charge = $+1 \left(\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1 \right)$.

A **neutron** is made up of **1 up quark and 2 down quarks**. No charge $\left(\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0 \right)$.

Mesons are made up of **2** quarks. They always consist of a quark and an anti-quark pair.

An example of a meson is a negative pion ($\pi^- = \bar{u} d$). It is made up of an anti-up quark and a down quark: This gives it a charge of $-\frac{2}{3} - \frac{1}{3} = -1$.

Note: A bar above a quark represents an antiquark e.g. \bar{u} is the anti-up quark (this is **not** the same as the down quark.) The negative pion only has a lifetime of around 2.6×10^{-8} s

Fundamental particles

The 6 quarks and 6 leptons are all believed to be **fundamental particles**. That is physicists believe that they are not made out of even smaller particles. It is possible that future experiments may prove this statement to be wrong, just as early 20th Century scientists thought that the proton was a fundamental particle.

Forces and bosons

Why does the nucleus not fly apart? If all the protons within it are positively charged then electrostatic repulsion should make them fly apart. There must be another force holding them together that, over the short range within a nucleus, is stronger than the electrostatic repulsion. This force is called the strong nuclear force. As its name suggests, it is the strongest of the four fundamental forces but it is also extremely short range in action. It is also only experienced by quarks and therefore by the baryons and mesons that are made up from them.

The weak nuclear force is involved in radioactive beta decay. It is called the weak nuclear force to distinguish it from the strong nuclear force, but it is not actually the weakest of all the fundamental forces. It is also an extremely short-range force.

The final two fundamental forces are gravitational and electromagnetic forces, the latter being described by James Clerk Maxwell's successful combination of electrostatic and magnetic forces in the 19th century. Both these forces have infinite range.

This is the current understanding of the fundamental forces that exist in nature. It may appear surprising that gravity is, in fact, the weakest of all the fundamental forces when we are so aware of its effect on us in everyday life. However, if the electromagnetic and strong nuclear forces were not so strong then all matter would easily be broken apart and our universe would not exist in the form it does today.

Force	Range (m)	Relative strength	Approximate decay time (s)	Example effects
Strong nuclear	10^{-15}	10^{38}	10^{-23}	Holding neutrons in the nucleus
Weak nuclear	10^{-18}	10^{25}	10^{-10}	Beta decay; decay of unstable hadrons
Electromagnetic	∞	10^{36}	10^{-20} – 10^{-16}	Holding electrons in atoms
Gravitational	∞	1	Undiscovered	Holding matter in planets, stars and galaxies

At an everyday level we are familiar with contact forces when two objects are touching each other. Later in this unit you will consider electric fields as a description of how forces act over a distance. At a microscopic level we use a different mechanism to explain the action of forces; this uses something called exchange particles. Each force is mediated through an exchange particle or boson.

Consider a macroscopic analogy. The exchange particles for the four fundamental forces are given in the table below and most of these form part of the standard model. Much work has been done over the last century to find theories that combine these forces (just like Maxwell showed that the same equations could be used to describe both electrostatic and magnetic forces). There has been much success with quantum electrodynamics in giving a combined theory of electromagnetic and weak forces. Much work has also been done to combine this with the strong force to provide what is known as a grand unified theory. Unfortunately, gravity is proving much more difficult to incorporate consistently into current theories, to produce what would be known as a 'theory of everything', therefore gravity is not included in the standard model. So far this has not caused significant problems because the relative weakness of gravity and the tiny mass of subatomic particles means that it does not appear to be a significant force within the nucleus.

Force	Exchange particle
Strong nuclear	Gluon
Weak nuclear	W and Z bosons
Electromagnetic	Photon
Gravitational	Graviton*

*Not yet verified experimentally.

Many theories postulated the existence of a further boson, called the Higgs boson after Peter Higgs of Edinburgh University. The Higgs boson is not involved in forces but is what gives particles mass. The discovery of a particle, or particles, matching the description of the Higgs boson was announced at CERN on 4th July 2012.

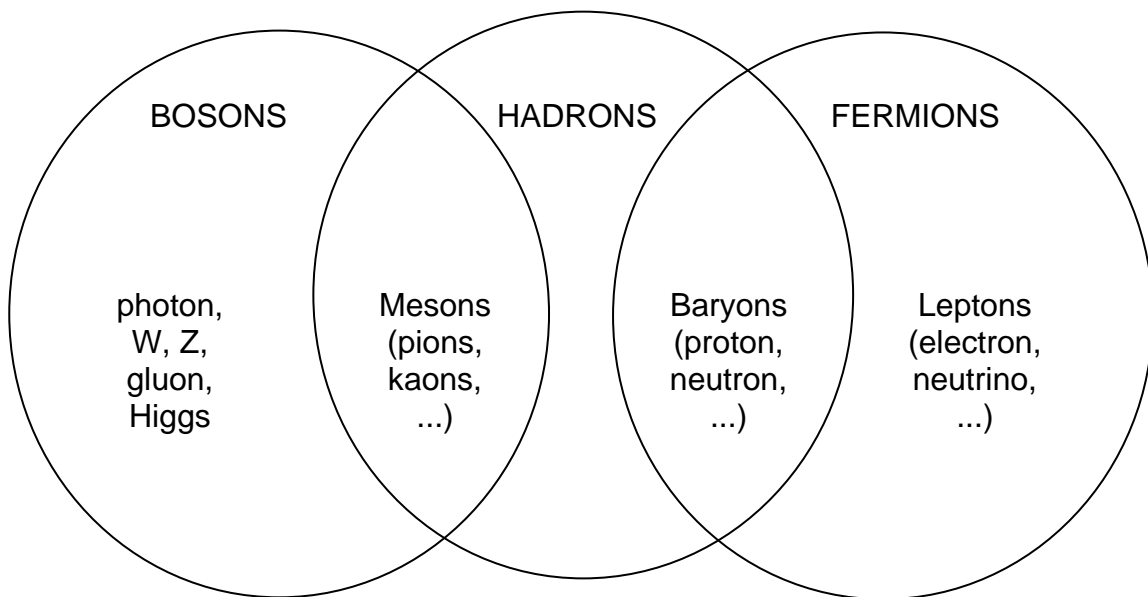
Standard model summary

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] weak force

Bosons (Forces)

Classification of particles



For example, a proton is both a fermion (a matter particle) and a hadron (a particle made up of quarks).

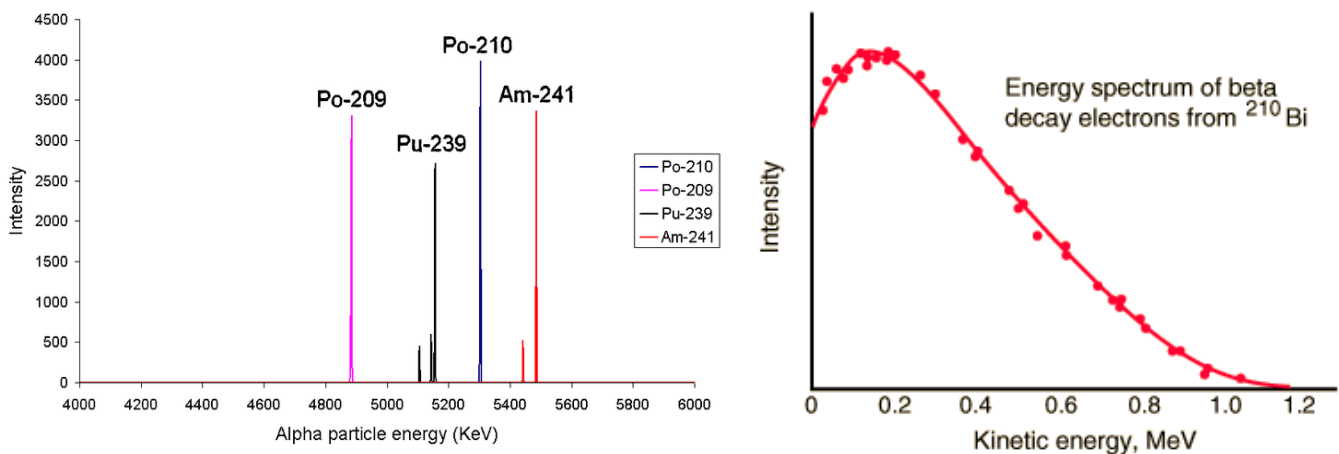
Beta decay and the antineutrino

Neutrinos were first discovered in radioactive beta decay experiments.

In beta decay, a neutron in the atomic nucleus decays into a proton and an electron (at a fundamental level, a down quark decays into an up quark through the emission of a W^- boson). The electron is forced out at high speed due to the nuclear forces. This carries away kinetic energy (and momentum). Precise measurement of this energy has shown that there is a continuous spread of possible values.

This result was unexpected because when alpha particles are created in alpha decay they have very precise and distinct energies. This energy corresponds to the difference in the energy of the nucleus before and after the decay.

The graphs below show the energy of alpha particles emitted by the alpha decay of protactinium-231 (left) and the energy of electrons emitted by beta decay of bismuth-210 (right).



It is clear that the process that creates the beta decay electrons is different from alpha decay. The electrons in beta decay come out with a range of energies up to, but not including the expected value.

To solve this problem, it was proposed that there must be another particle emitted in the decay which carried away with it the missing energy and momentum. Since this had not been detected, the experimenters concluded that it must be neutral and highly penetrating. This was the first evidence for the existence of the neutrino. (In fact, in beta decay an anti-neutrino is emitted along with the electron as lepton number is conserved in particle reactions. There is another type of beta decay, β^+ , which has a certain symmetry with the β^- decay above. In this process a proton decays into a neutron, and a positron and a neutrino are emitted.)

Interesting fact

More than 50 trillion (50×10^{12}) solar neutrinos pass through an average human body *every second* while having no measurable effect. They interact so rarely with matter that detectors consisting of massive tanks of water, deep underground and therefore screened from cosmic rays, are required to detect them.

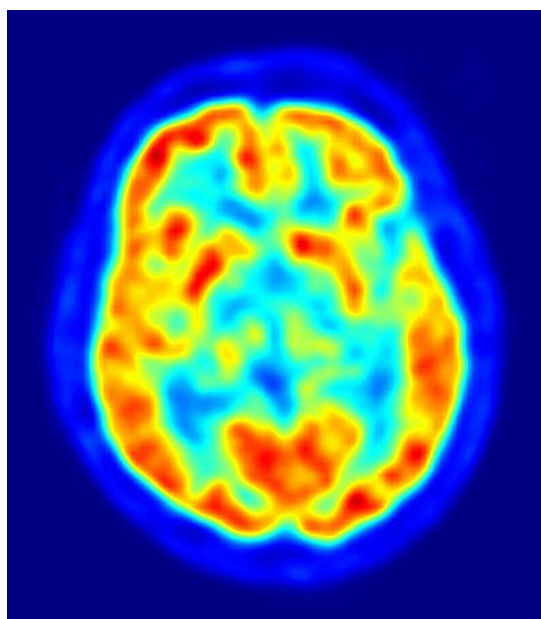
Practical uses of antimatter: positron emission tomography (PET) scanning

Positron emission tomography scanners use antimatter annihilation to obtain detailed 3-D scans of body function. Other imaging techniques called computed tomography (CT) which use X-rays and magnetic resonance imaging (MRI) can give detailed pictures of the bone and tissue within the body but PET scans give a much clearer picture of how body processes are actually working.

A β^+ tracer with a short half-life is introduced into the body attached to compounds normally used by the body, such as glucose, water or oxygen. When this tracer emits a positron it will annihilate nearly instantaneously with an electron. This produces a pair of gamma-ray photons of specific frequency moving in approximately opposite directions to each other. (The reason it is only an approximately opposite direction is that the positron and electron are moving before the annihilation event takes place.) The gamma rays are detected by a ring of scintillators, each producing a burst of light that can be detected by photomultiplier tubes or photodiodes. Complex computer analysis traces tens of thousands of possible events each second and the positions of the original emissions are calculated. A 3-D image can then be constructed, often along with a CT or MRI scan to obtain a more accurate picture of the anatomy alongside the body function being investigated.

Tracing the use of glucose in the body can be used in oncology (the treatment of cancer) since cancer cells take up more glucose than healthy ones. This means that tumours appear bright on the PET image. Glucose is also extremely important in brain cells, which makes PET scans very useful for investigation into Alzheimer's and other neurological disorders. If oxygen is used as the tracking molecule, PET scans can be used to look at blood flow in the heart to detect coronary heart disease and other heart problems.

The detecting equipment in PET scanners has much in common with particle detectors and the latest developments in particle accelerators can be used to improve this field of medical physics.



Forces on Charged Particles

Electric charge

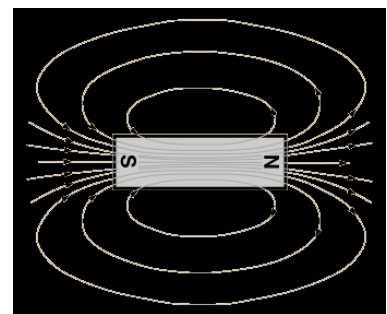
Electric charge has the symbol Q and is measured in coulombs (C).

The charge on a proton is 1.60×10^{-19} C. The charge on an electron has the same magnitude but is opposite in sign, i.e. -1.60×10^{-19} C.

Like charges repel (i.e. $+/+$ or $-/-$). Opposite charges attract (i.e. $+/-$ or $-/+$). For the charges to experience a **change in motion**, they must experience an **unbalanced force**. Physicists use the concept of a force **field** in order to describe and explain the forces on charges.

In physics, a **field** means a region where an object experiences a force.

For example, there is a **gravitational field** around the Earth. This attracts **mass** towards the centre of the Earth. Gravitational field strength at a point is a measure of the gravitational force acting on a mass of 1 kg at that point.



Magnets are surrounded by **magnetic fields**.

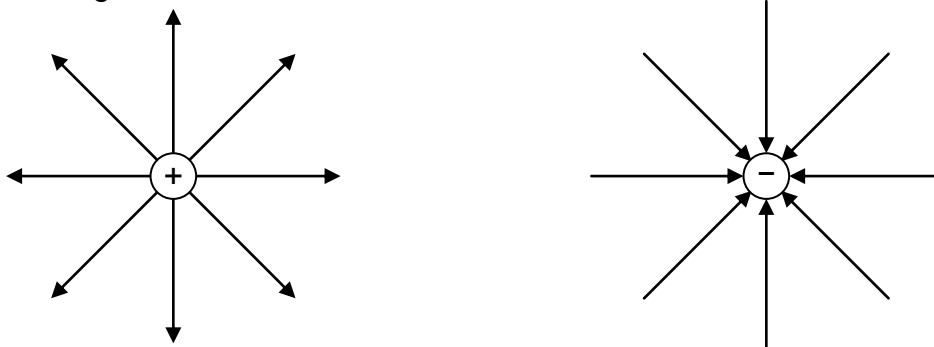
This creates a force on other magnets and certain other materials.

Electric Fields

Electric charges are surrounded by an **electric field** (this is not the same as a magnetic field). In an electric field, a charged particle experiences an electric force. The electric field strength at a point is a measure of the electric force acting on a charge of +1 C at that point.

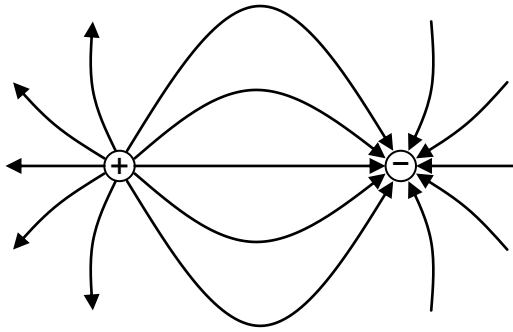
The direction of an electric field is the direction of the force that a positive charge experiences in the field. Electric field lines therefore always start on positive charges and end on negative charges.

Isolated point charges:

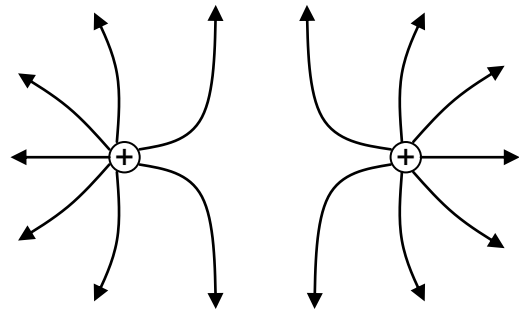


These are examples of radial fields. The lines are like the radii of a circle. The strength of the field decreases further away from the charge. The relationship is similar to the gravitational field around a planet.

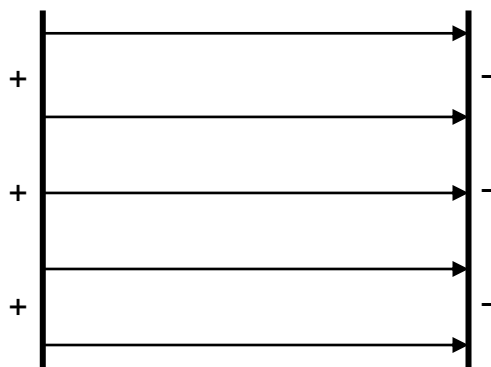
Unlike point charges:



Like point charges:



Parallel charged plates:



The electric field between parallel charged plates is uniform. The strength of the electric field does not vary and this is represented by the parallel, equally spaced field lines.

Movement of charge in an electric field, p.d. and electrical energy

Comparison between gravitational fields and electric fields

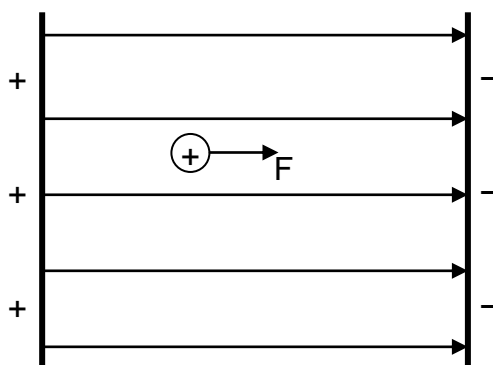
Movement of a mass in a gravitational field

If a tennis ball is released in a gravitational field such as on Earth, a force is exerted on it. The force acts in the direction of the gravitational field and as a result the ball accelerates downwards. Close to the surface of the Earth, the acceleration (and therefore the unbalanced force on the ball) is constant. The gravitational field is therefore described as a uniform field.



Movement of a charge in an electric field

Consider a small, positively charged particle in an electric field as shown:



When the charge is released between the parallel plates a force is exerted on it. As it is a positive charge, the force acts in the direction of the electric field. It accelerates towards the negative plate.

The electric field is a uniform field. This is shown by the uniform spacing of the straight field lines. The unbalanced force is therefore constant, resulting in uniform acceleration.

There is a strong similarity between the motion of a small positive charge in an electric field and a tennis ball in a gravitational field.

Comparison between gravitational and electrostatic potential energy

Gravitational potential energy

Work must be done to raise an object against the direction of the gravitational force and this energy is stored in the gravitational field as gravitational potential energy.

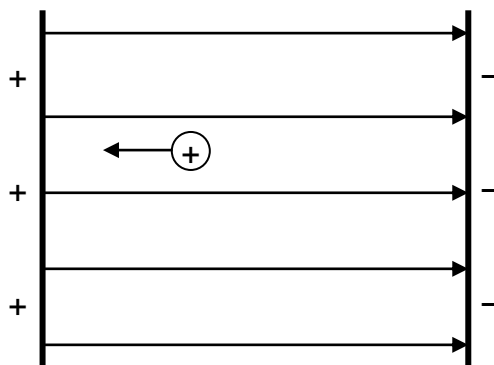
work done lifting the ball against the field = the gain in gravitational potential energy

If the ball is released there is a transfer of this potential energy to kinetic energy, i.e. the ball moves. The kinetic energy of the ball can be calculated by using the conservation of energy.

$$E_P = E_K$$
$$mgh = \frac{1}{2}mv^2$$

Electrostatic potential energy

Consider the small positive charge moved **against** the field as shown.



This is equivalent to lifting a tennis ball against the gravitational field. Work must be done to move the charge against the direction of force. When held in place, the small positive charge is an **electrostatic potential store of energy**.

work done moving the charge against the field = the gain in electrical potential energy

Definition of potential difference and the volt

Potential difference (p.d.) is defined to be a measure of the work done in moving one coulomb of charge between two points in an electric field. Potential difference (p.d.) is often called voltage. This gives the definition of the volt.

There is a potential difference of 1 volt between two points if 1 joule of energy is required to move 1 coulomb of charge between the two points, $1 \text{ V} = 1 \text{ J C}^{-1}$.

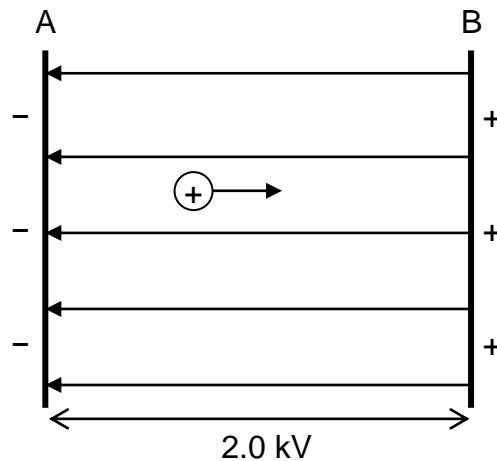
This relationship can be written mathematically: $E_w = QV$ or $V = \frac{E_w}{Q}$

where E_w is energy (work done) in joules (J), Q is the charge in coulombs (C) and V is the potential difference (p.d.) in volts (V).

If the small positive charge, above, is released there is a transfer of energy to kinetic energy, i.e. the charge moves. Again, using the conservation of energy means that:

$$\begin{aligned} E_w &= E_K \\ QV &= \frac{1}{2}mv^2 \end{aligned}$$

Example: A positive charge of $3.0 \mu\text{C}$ is moved from A to B. The potential difference between A and B is 2.0 kV .



- Calculate the electric potential energy gained by the charge–field system.
- The charge is released. Describe the motion of the charge.
- Determine the kinetic energy when the charge is at point A.
- The mass of the charge is 5.0 mg . Calculate the speed of the charge.

Solution:

$$\begin{aligned} \text{(a)} \quad Q &= 3.0 \mu\text{C} = 3.0 \times 10^{-6} \text{ C} \\ V &= 2.0 \text{ kV} = 2.0 \times 10^3 \text{ V} \\ E_w &= ? \end{aligned}$$

$$\begin{aligned} E_w &= QV \\ E_w &= 3.0 \times 10^{-6} \times 2.0 \times 10^3 \\ E_w &= 6.0 \times 10^{-3} \text{ J} \end{aligned}$$

(b) The electric field is uniform so the charge experiences a constant unbalanced force. The charge accelerates uniformly towards the negative plate A.

$$\text{(c)} \quad \text{By conservation of energy, } E_K = E_w = 6.0 \times 10^{-3} \text{ J}$$

$$\begin{aligned} \text{(d)} \quad m &= 5.0 \text{ mg} = 5.0 \times 10^{-6} \text{ kg} \\ E_K &= 6.0 \times 10^{-3} \text{ J} \\ v &= ? \end{aligned}$$

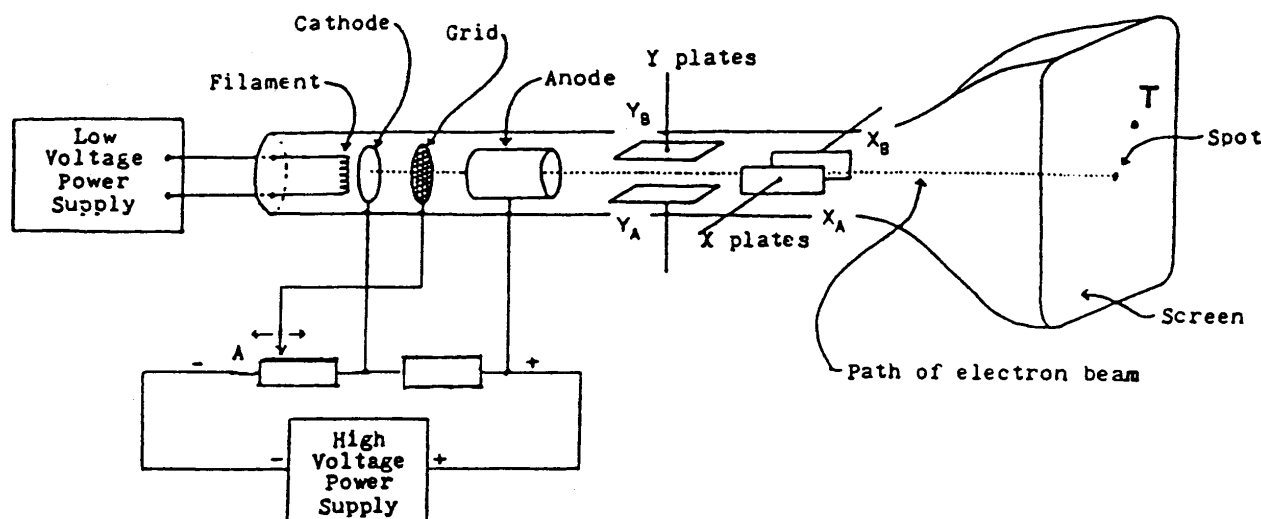
$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ 6.0 \times 10^{-3} &= 0.5 \times 5.0 \times 10^{-6} \times v^2 \\ v^2 &= 2.4 \times 10^{-3} \\ v &= 49 \text{ m s}^{-1} \end{aligned}$$

Applications of electric fields

Cathode ray tubes

The cathode ray tube (CRT) was invented in the 1800s but formed the basis of the majority of the world's new television technology until the mid-2000s. The cathode ray tube continues to be the basis for some scientific equipment such as the oscilloscope and radar systems. In the CRT an "electron gun" fires electrons at a screen.

A cathode ray tube in an oscilloscope:



Electrons, excited by heat energy from the filament, are emitted by the cathode and are accelerated forwards through a large potential difference towards the anode. The electrons pass through the cylindrical anode and a beam is formed. The grid is negative with respect to the cathode and some of the electrons are repelled back towards the cathode. It is made more negative by moving the variable resistor control towards A, more electrons will be repelled and so the beam becomes less intense and the spot dimmer.

Potential differences applied to pairs of parallel plates are used to deflect the electron beam to different points on the screen. For the spot to be deflected to point T then plate Y_B must be more positive than plate Y_A and plate X_B must be more positive than plate X_A .

We can use this to calculate the speed of an electron within the electron gun as shown in the following example.

Example: An electron is accelerated from rest through a potential difference of 200 V.

Calculate:

- the kinetic energy of the electron;
- the final speed of the electron.

(Note: in an exam, the mass and charge of the electron can be found on the data sheet.)

Solution:

(a) $Q = 1.60 \times 10^{-19} \text{ C}$
 $V = 200 \text{ V}$
 $E_K = ?$

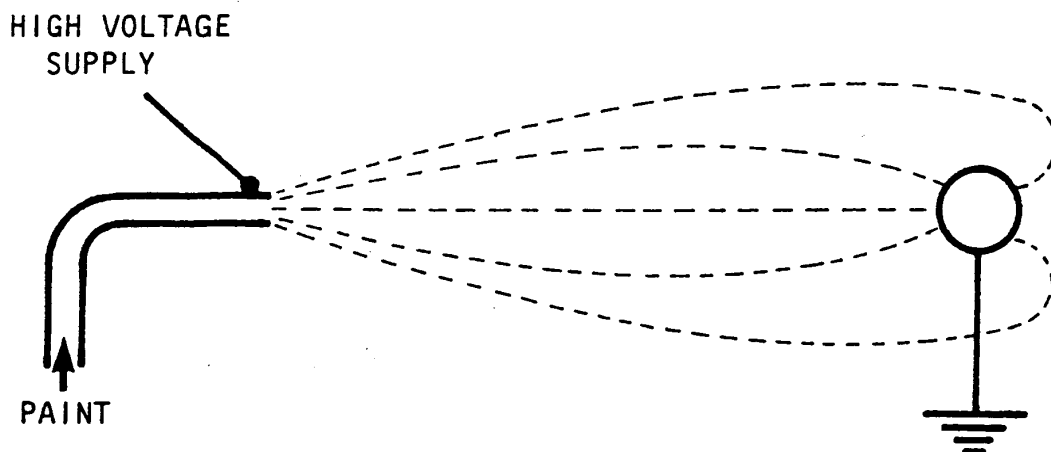
$E_K = E_w$ by the electric field
 $E_K = QV$
 $E_K = 1.60 \times 10^{-19} \times 200$
 $E_K = 3.20 \times 10^{-17} \text{ J}$

(b) $m = 5.0 \text{ mg} = 9.11 \times 10^{-31} \text{ kg}$
 $E_K = 3.20 \times 10^{-17} \text{ J}$
 $v = ?$

$E_K = \frac{1}{2}mv^2$
 $3.20 \times 10^{-17} = 0.5 \times 9.11 \times 10^{-31} \times v^2$
 $v^2 = 7.025 \times 10^{13}$
 $v = 8.38 \times 10^6 \text{ m s}^{-1}$

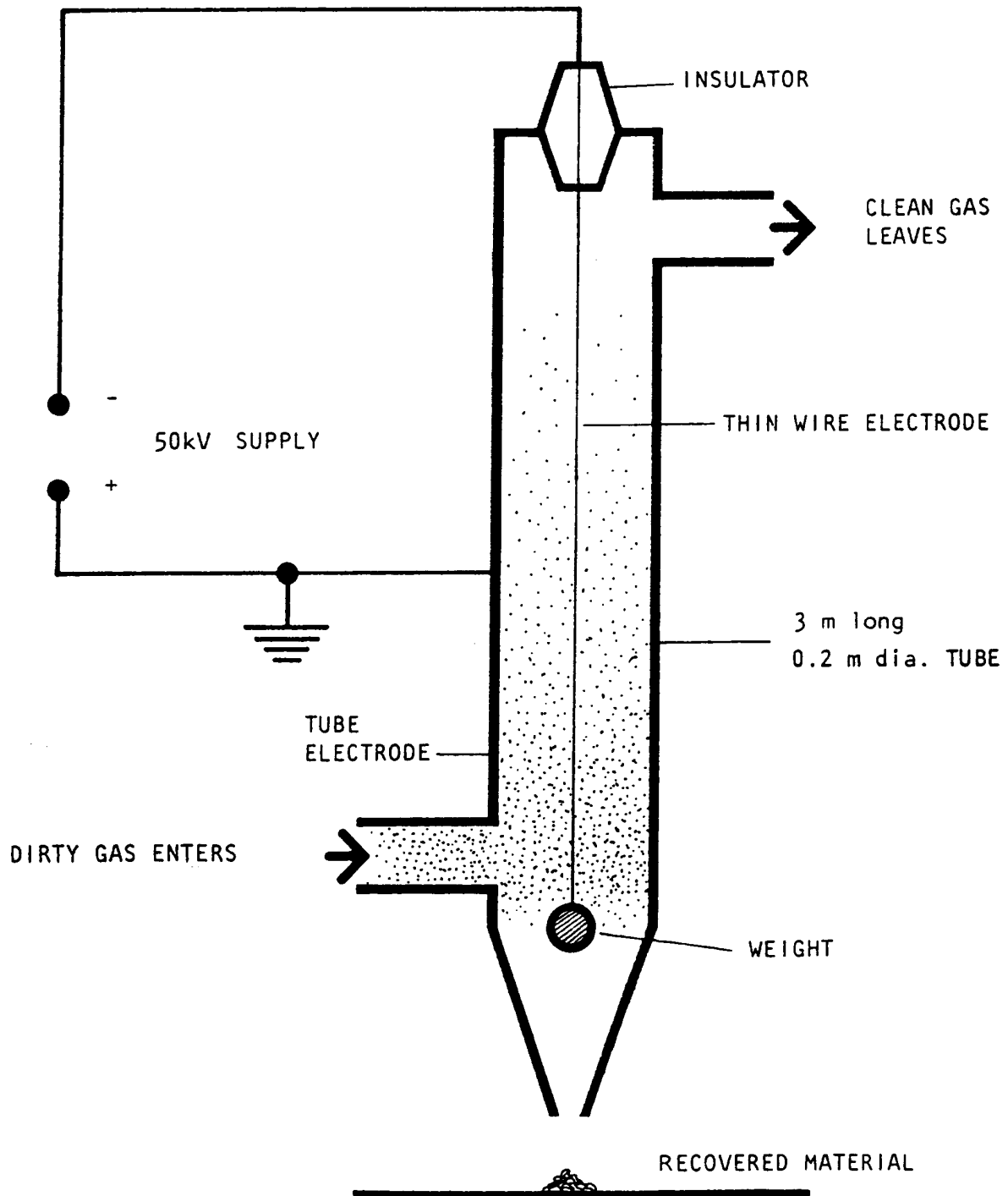
Paint spraying

Conducting objects, such as metal stool frames, bike frames and car bodies, can be painted efficiently by charging the paint spray so that most paint is attracted to the conductor. This method can even be used to paint the back of the conductor.



Electrostatic precipitation

This is the process by which solid or liquid particles can be removed from a gaseous carrying medium by giving them an electric charge and then precipitating them on to a suitable receiving surface in an electric field. This process is used to remove "fly-ash" from power station flues.



Charged Particles in Magnetic Fields

The discovery of the interaction between electricity and magnetism, and the resultant ability to produce movement, must rank as one of the most significant developments in physics in terms of the impact on everyday life.

This work was first carried out by Michael Faraday whose work on electromagnetic rotation in 1821 gave us the electric motor. He was also involved in the work which brought electricity into everyday life, with the discovery of the principle of the transformer and generator in 1831. Not everyone could see its potential. William Gladstone (1809–1898), the then Chancellor of the Exchequer and subsequently four-time Prime Minister of Great Britain, challenged Faraday on the practical worth of this new discovery – electricity. Faraday's response was 'Why, sir, there is every probability that you will soon be able to tax it!' The Scottish physicist, James Clerk Maxwell (1831–1879), built upon the work of Faraday and wrote down mathematical equations describing the interaction between electric and magnetic fields. The computing revolution of the 20th century could not have happened without an understanding of electromagnetism.

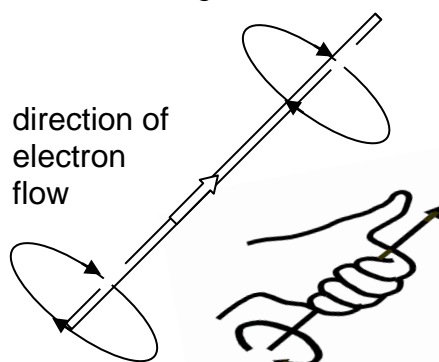
The last section introduced the idea that an electric field that surrounds a stationary electric charge. This section answers the following questions:

- What happens when a charged particle is on the move?
- How does a motor work?

Moving charges create magnetic fields

In 1820 the Danish physicist Oersted discovered that a magnetic compass was deflected when an electrical current flowed through a nearby wire. This was explained by saying that when a charged particle moves a magnetic field is generated. In other words, a wire with a current flowing through it (a current-carrying wire) creates a magnetic field.

The magnetic field around a current-carrying wire is circular. For electron flow, the direction of the field can be found by using the left-hand grip rule.



Summary

A **stationary charge** creates an **electric field**.

A **moving charge** also creates a **magnetic field**.

Moving charges experience a force in a magnetic field

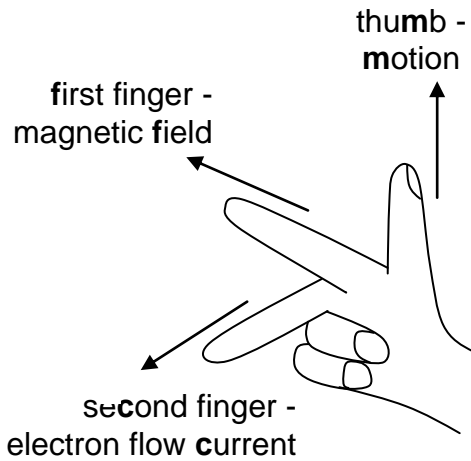
A magnetic field surrounds a magnet. When two magnets interact, they attract or repel each other due to the interaction between the magnetic fields surrounding each magnet.

A moving electric charge behaves like a mini-magnet as it creates its own magnetic field. This means it experiences a force if it moves through an external magnetic field (in the same way that a mass experiences a force in a gravitational field or a charge experiences a force in an electric field.)

Simple rules can be used to determine the direction of force on a charged particle in a magnetic field.

Movement of a negative charge in a magnetic field

One common method is known as **the right-hand motor rule**.



motor effect – right hand

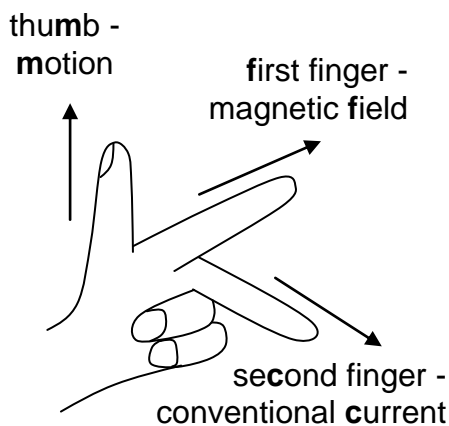
first finger – direction of the magnetic field

second finger – direction of the electron flow current

thumb – direction of motion

Movement of a positive charge in a magnetic field

One common method is known as **Fleming's left-hand motor rule**.

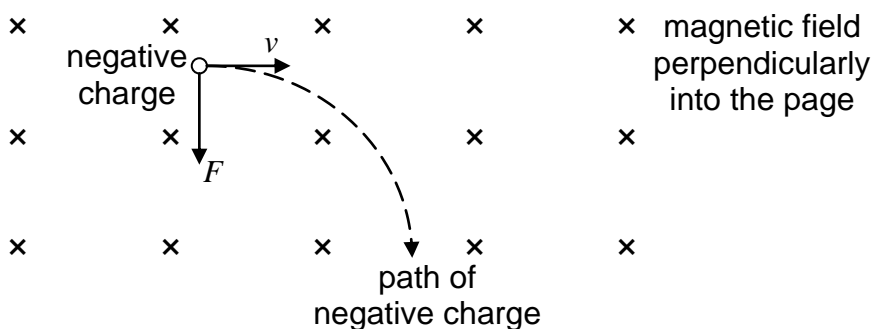


motor effect – left hand

first finger – direction of the magnetic field

second finger – direction of the conventional current

thumb – direction of motion

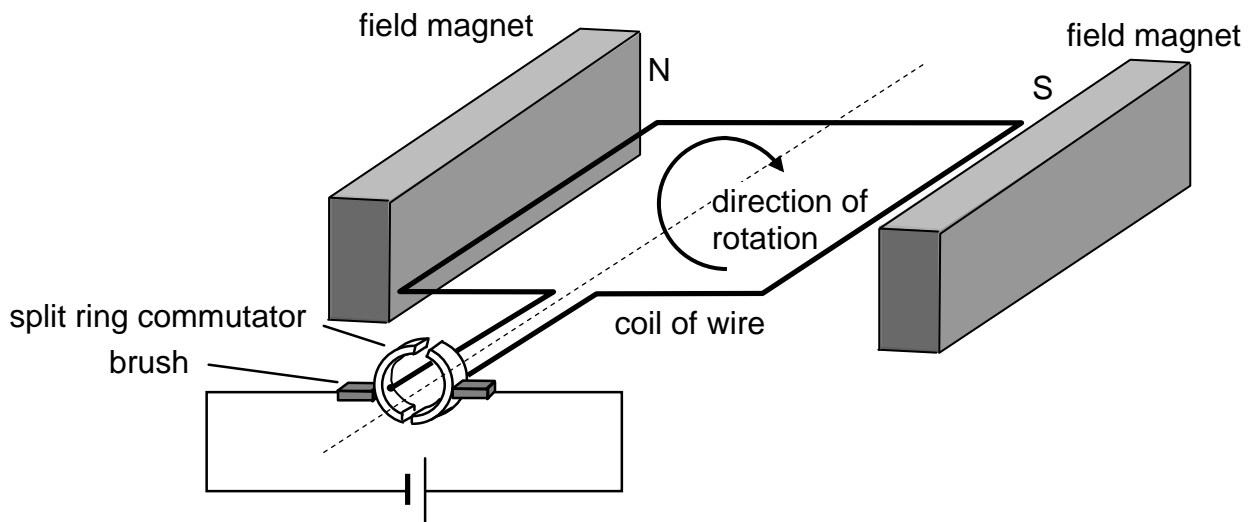


The motor rules are also used to determine the direction of spin of the coil in an electric motor.

The Electric Motor

When a current-carrying wire is placed between the poles of a permanent magnet, it experiences a force. The direction of the force is at right-angles to:

- the direction of the current in the wire;
- the direction of the magnetic field of the permanent magnet.



An electric motor must spin continuously in the same direction. Whichever side of the coil is nearest the north pole of the field magnets above must always experience an upwards force if the coil is to turn clockwise. That side of the coil must therefore always be connected to the negative terminal of the power supply. Once the coil reaches the vertical position the ends of the coil must be connected to the opposite terminals of the power supply to keep the coil turning. This is done by split ring commutator.

In order for the coil to spin freely there cannot be permanent fixed connections between the supply and the split ring commutator. Brushes rub against the split ring commutator ensuring that a good conducting path exists between the power supply and the coil regardless of the position of the coil.

Particle Accelerators

Particle accelerators are used to probe matter. They have been used to determine the structure of matter and investigate the conditions soon after the Big Bang. Particle accelerators are also used produce a range of electromagnetic radiations which can be used in many other experiments.

There are three main types of particle accelerators:

- linear accelerators
- cyclotrons
- synchrotrons

Regardless of whether the particle accelerator is linear or circular, the basic parts are the same:

- **a source of particles** (these may come from another accelerator)
Accelerators using electrons use thermionic emission in the same way as a cathode ray tube. At the Large Hadron Collider (LHC) at CERN the source of particles is simply a bottle of hydrogen gas. Electrons are stripped from the hydrogen atoms leaving positively charged protons. These are then passed through several smaller accelerator rings before they reach the main beam pipe of the LHC.
- **beam pipes** (also called the **vacuum chamber**)
Beam pipes are special pipes which the particles travel through while being accelerated. There is a **vacuum** inside the pipes which ensures that the beam particles do not collide with other atoms such as air molecules.
- **accelerating structures** (a method of accelerating the particles)
As the particles speed around the beam pipes they enter special accelerating regions where there is a **rapidly changing electric field**. At the LHC, as the protons approach the accelerating region, the electric field is negative and the protons accelerate towards it. As they move through the accelerator, the electric field becomes positive and the protons are repelled away from it. In this way the protons increase their kinetic energy and they are accelerated to almost the speed of light.
- **a system of magnets** (electromagnets or superconducting magnets as in the LHC)
Newton's first law states that an object travels with a constant velocity (both speed and direction) unless acted on by an external force. The particles in the beam pipes would go in a straight line if they were not constantly going past powerful, fixed magnets which cause them to travel in a circle. There are over 9000 superconducting magnets at the LHC in CERN. These operate best at temperatures very close to the absolute 0K and this is why the whole machine needs to be cooled down. If superconducting magnets were not used, they would not be able to steer and focus the beam within such a tight circle and so the energies of the protons which are collided would be much lower.
- **a target**
In some accelerators the beam collides directly with a stationary target, such as a metal block. In this method, much of the beam energy is simply transferred to the block instead of creating new particles. In the LHC, the target is an identical bunch of particles travelling in the opposite direction. The two beams are brought together at four special points on the ring where massive detectors are used to analyse the collisions.

Nuclear Reactions

To examine nuclear reactions it is necessary to define a number of terms used to describe a nucleus.

Nucleon

A nucleon is a particle in a nucleus, i.e. either a proton or a neutron.

Atomic Number

The atomic number, Z , equals the number of protons in the nucleus. In a chemical symbol for an element it is written as a subscript before the element symbol.

Example: There are 92 protons in the nucleus of a uranium atom so we write ${}_{92}\text{U}$

Mass Number

The mass number, A , is the number of nucleons in a nucleus. In a chemical symbol for an element it is written as a superscript before the element symbol.

Example: One type of atom of uranium has 235 nucleons so we write ${}^{235}\text{U}$.

Nuclide

A nuclide is a nucleus with a specific number of protons and neutrons.

Example 1: One type of helium atom contains two protons and two neutrons. Its nuclide symbol is ${}^4_2\text{He}$.

Example 2: ${}^{220}_{86}\text{Rn}$ is the nuclide of radon containing 86 protons and $220 - 86 = 134$ neutrons.

Isotope

Isotopes are nuclides of the same atomic number but different mass numbers, i.e. nuclei containing the same number of protons but different numbers of neutrons.

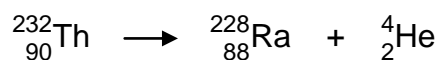
Example: ${}^{12}_6\text{C}$ the most common isotope of carbon and contains 6 protons and 6 neutrons.
 ${}^{14}_6\text{C}$ is a less common radioactive isotope (radioisotope) of carbon and contains 6 protons and 8 neutrons.

Radioactive Decay

Alpha Emission

In 1909 Rutherford and Royds proved that α -particles were helium nuclei. An α -particle has two protons and two neutrons and so the emission of an α -particle from a nucleus must form a daughter with an atomic number decreased by two and a mass number decreased by four.

Example: In the alpha decay of Thorium-232, the daughter product is Radium-228.



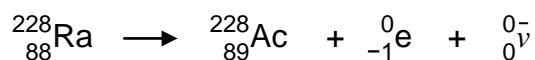
Beta Emission

The β -particle is a very fast moving electron emanating from the nucleus. It has the symbol ${}_{-1}^0\text{e}$.

In a beta decay a neutron in the nucleus changes into a proton, an electron and an antineutrino.



Example: In the beta decay of Radium-228, the daughter product is Actinium-228.



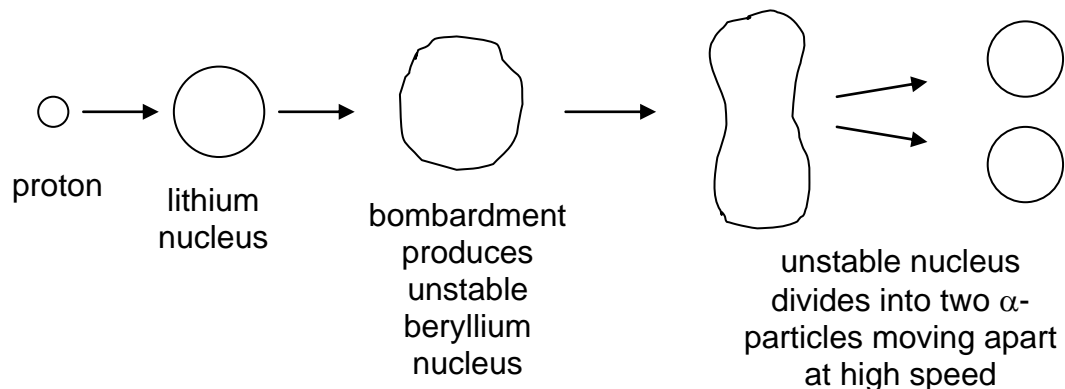
Note that the mass number remains unaltered but the atomic number increases by 1.

Gamma Emission

Changes in the internal structure of a nucleus can cause the release of large quantities of electromagnetic radiation. This radiation has a high frequency and is called γ -radiation.

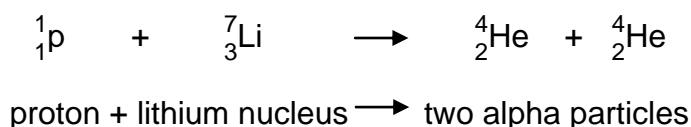
The emission of α , β and γ radiations from radioactive nuclei occurs in a random manner and is a natural process over which scientists have no control. Earlier this century physicists found they could “break up” atomic nuclei by bombarding them with other particles.

One experiment involved bombarding lithium nuclei with hydrogen nuclei (protons).



The splitting of the nucleus in this way is called nuclear **fission**.

The fission of the lithium nucleus can be represented as follows:



Physicists, using a piece of apparatus called a mass spectrometer, are able to measure the masses of the particles involved in the reaction very accurately. It is found that the mass of the particles after the reaction is less than the mass of the particles before the reaction.

Before:	proton	1.673 $\times 10^{-27}$ kg
	lithium	11.650 $\times 10^{-27}$ kg
	total mass	13.323 $\times 10^{-27}$ kg
After:	α -particle	6.646 $\times 10^{-27}$ kg
	α -particle	6.646 $\times 10^{-27}$ kg
	total mass	13.292 $\times 10^{-27}$ kg

If energy changes are also taken into account then the reaction can be represented as follows:

The kinetic energy of the α -particles is found to be much greater than the initial kinetic energy of the proton. The loss of mass has been accompanied by a huge increase in energy.

Einstein linked the loss of mass with the increase in energy using the equation:

$$E = mc^2$$

For the reaction shown above the loss of mass is $(13.323 - 13.292) \times 10^{-27} \text{ kg}$
 $= 0.031 \times 10^{-27} \text{ kg}$

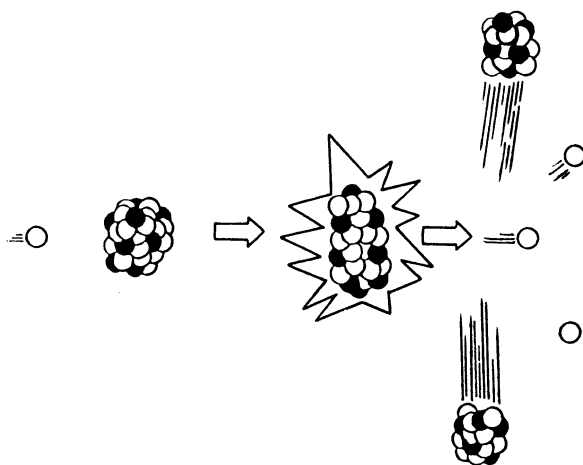
The energy released by this reaction is given by $E = mc^2$
 $= 0.031 \times 10^{-27} \times (3.0 \times 10^8)^2 \text{ kg}$
 $= 2.79 \times 10^{-10} \text{ J}$

Example: When a β -particle is emitted by a nuclide a neutron has given rise to a proton and an electron. The mass of a neutron is $1.6748 \times 10^{-27} \text{ kg}$. The mass of a proton is $1.6725 \times 10^{-27} \text{ kg}$. The mass of an electron is $9 \times 10^{-31} \text{ kg}$.

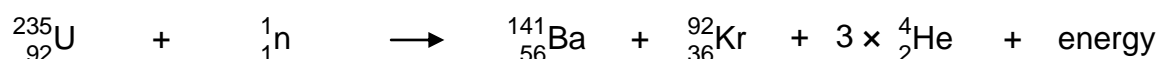
Calculate the energy produced by this reaction.

Fission

The possibility of fission as a nuclear reaction is greatest for nuclei of high nucleon number. The diagram below illustrates the fission of a uranium-235 nucleus by a slow (low energy) neutron.



The nuclear reaction may be represented by:



uranium-235 nucleus + neutron \longrightarrow barium-141 nucleus + krypton 92 nucleus + 3 neutrons + energy

It is found that the total mass of the particles after the reaction is less than that before the reaction.

The loss of mass results in the release of energy.

Mass before fission (m_1):	uranium	390.274×10^{-27} kg
	neutron	1.675×10^{-27} kg
	total	391.949×10^{-27} kg

Mass after fission (m_2):	barium	233.978×10^{-27} kg
	krypton	152.610×10^{-27} kg
	3 x neutrons	5.025×10^{-27} kg
	total	391.613×10^{-27} kg

Loss of mass ($m_1 - m_2$):	Δm	0.336×10^{-27} kg
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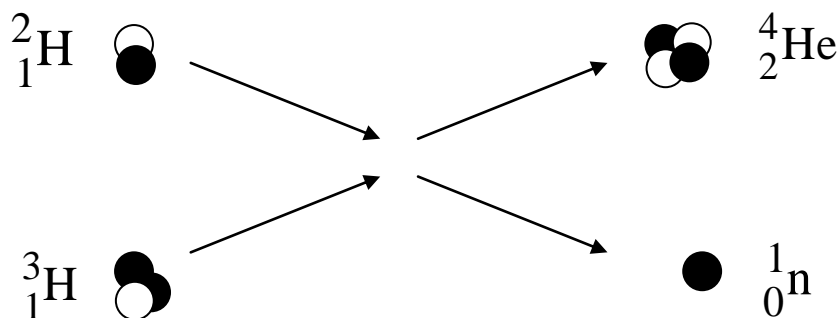
$$\begin{aligned} \text{Energy released} \quad E &= mc^2 \\ &= 0.336 \times 10^{-27} \times (3.0 \times 10^8)^2 \\ &= 3.0 \times 10^{-11} \text{ J} \end{aligned}$$

It is possible that the neutrons released in the reaction can go on to produce further fission reactions resulting in a chain reaction. The large amount of energy released can be harnessed in a nuclear power station and used to boil water to generate electricity.

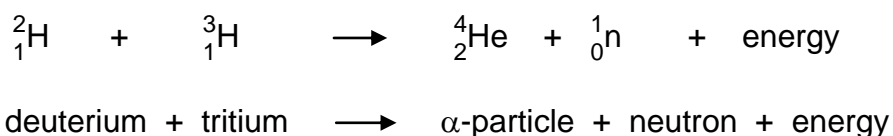
Fusion

Fusion occurs when two light nuclei combine to form a nucleus of larger mass number.

The diagram illustrates the fusion of deuterium ${}^2_1\text{H}$ and tritium ${}^3_1\text{H}$.



The nuclear reaction can be represented by:



Once again it is found that the total mass after the reaction is less than the total mass before. This reduction in mass appears as an increase in the kinetic energy of the particles.

Mass before fusion (m_1):	deuterium	3.345×10^{-27} kg
	tritium	5.008×10^{-27} kg
	total	8.353×10^{-27} kg

Mass after fusion (m_2):	α -particle	6.647×10^{-27} kg
	neutron	1.675×10^{-27} kg
	total	8.322×10^{-27} kg

Loss of mass ($m_1 - m_2$):	Δm	0.031×10^{-27} kg
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Energy released

$$\begin{aligned}
 E &= mc^2 \\
 &= 0.031 \times 10^{-27} \times (3.0 \times 10^8)^2 \\
 &= 2.8 \times 10^{-12} \text{ J}
 \end{aligned}$$

Large quantities of energy can be released only if millions of nuclei are fused at once. The sun releases its energy through vast numbers of hydrogen nuclei fusing into helium every second.

Nuclear Fusion Reactors

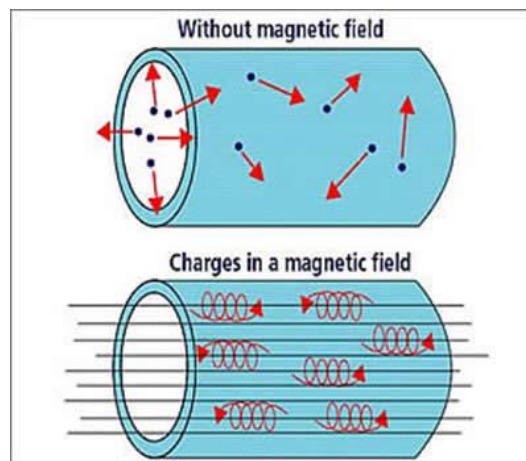
Fusion has been successfully achieved with the hydrogen bomb. However, this was an uncontrolled fusion reaction and the key to using fusion as an energy source is control.

The Joint European Torus (JET), in Oxfordshire, is Europe's largest fusion device. In this device, deuterium–tritium fusion reactions occur at over 100 million kelvin. Even higher temperatures are required for deuterium–deuterium and deuterium–helium 3 reactions.

To sustain fusion there are three conditions, which must be met simultaneously:

- plasma temperature (T): 100–200 million kelvin
- energy confinement time (t): 4–6 seconds
- central density in plasma (n): $1\text{--}2 \times 10^{20}$ particles m^{-3} (approx. 1 mg m^{-3} , i.e. one millionth of the density of air).

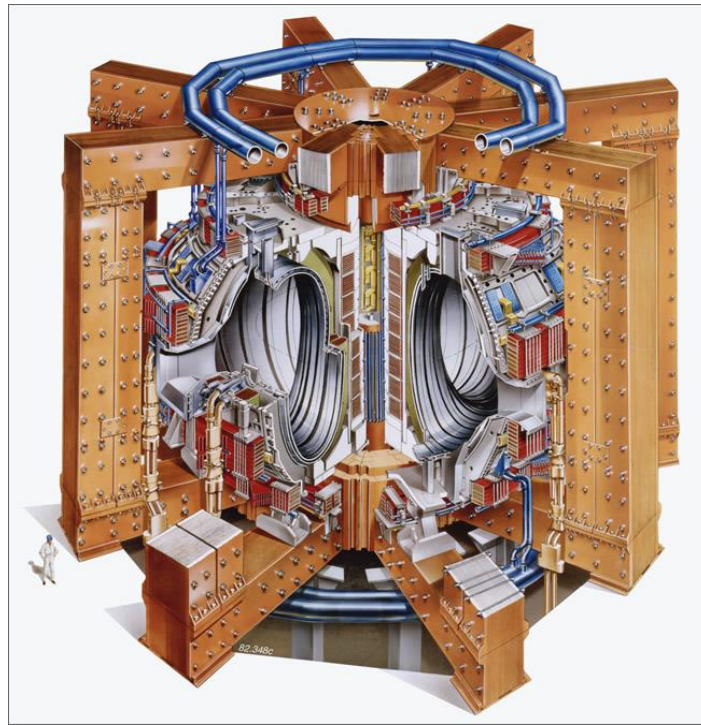
In a Tokamak the plasma is heated in a ring-shaped vessel (or torus) and kept away from the vessel walls by applied magnetic fields.



The basic components of the Tokamak's magnetic confinement system are:

- The toroidal field – which produces a field around the torus. This is maintained by magnetic field coils surrounding the vacuum vessel. The toroidal field provides the primary mechanism of confinement of the plasma particles.
- The poloidal field – which produces a field around the plasma cross-section. It pinches the plasma away from the walls and maintains the plasma's shape and stability. The poloidal field is induced both internally, by the current driven in the plasma (one of the plasma heating mechanisms), and externally, by coils that are positioned around the perimeter of the vessel.

The main plasma current is induced in the plasma by the action of a large transformer. A changing current in the primary winding or solenoid (a multi-turn coil wound onto a large iron core in JET) induces a powerful current (up to 5 million amperes on JET) in the plasma, which acts as the transformer secondary circuit.



One of the main requirements for fusion is to heat the plasma particles to very high temperatures or energies. The following methods are typically used to heat the plasma – all of them are employed on JET.

Ohmic heating and current drive

Currents up to 5 million amperes are induced in the JET plasma – typically via the transformer or solenoid. As well as providing a natural pinching of the plasma column away from the walls, the current inherently heats the plasma – by energising plasma electrons and ions in a particular toroidal direction. A few megawatts of heating power are provided in this way.

Neutral beam heating

Beams of high energy, neutral deuterium or tritium atoms are injected into the plasma, transferring their energy to the plasma via collisions with the plasma ions. The neutral beams are produced in two distinct phases. Firstly, a beam of energetic ions is produced by applying an accelerating voltage of up to 140,000 V. However, a beam of charged ions will not be able to penetrate the confining magnetic field in the Tokamak. Thus, the second stage ensures the accelerated beams are neutralised (i.e. the ions turned into neutral atoms) before injection into the plasma. In JET, up to 21 MW of additional power is available from the neutral beam injection heating systems.

Radio-frequency heating

As the plasma ions and electrons are confined to rotating around the magnetic field lines in the Tokamak, electromagnetic waves of a frequency matched to the ions or electrons are able to resonate – or damp its wave power into the plasma particles. As energy is transferred to the plasma at the precise location where the radio waves resonate with the ion/electron rotation, such wave heating schemes have the advantage of being localised at a particular location in the plasma.

In JET, a number of antennae in the vacuum vessel propagate waves in the frequency range of 25–55 MHz into the core of the plasma. These waves are tuned to resonate with particular ions in the plasma – thus heating them up. This method can inject up to 20 MW of heating power.

Waves can also be used to drive current in the plasma – by providing a ‘push’ to electrons travelling in one particular direction. In JET, 10 MW of these so-called lower hybrid microwaves (at 3.7 GHz) accelerate the plasma electrons to generate a plasma current of up to 3 MW.

Self-heating of plasma

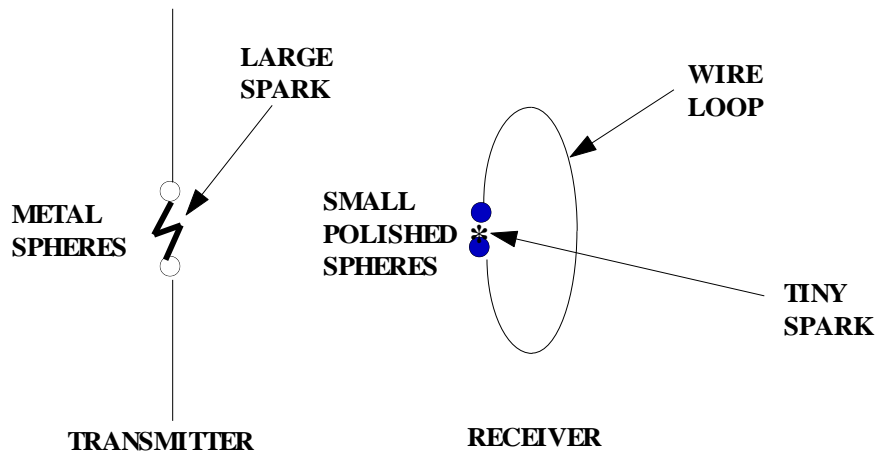
The helium ions (or so-called alpha-particles) produced when deuterium and tritium fuse remain within the plasma’s magnetic trap for a time, before they are pumped away through the diverter. The neutrons (being neutral) escape the magnetic field and their capture in a future fusion power plant will be the source of fusion power to produce electricity.

When fusion power output just equals the power required to heat and sustain plasma then breakeven is achieved. However, only the fusion energy contained within the helium ions heats the deuterium and tritium fuel ions (by collisions) to keep the fusion reaction going. When this self-heating mechanism is sufficient to maintain the plasma temperature required for fusion the reaction becomes self-sustaining (i.e. no external plasma heating is required). This condition is referred to as ignition. In magnetic plasma confinement of the deuterium–tritium fusion reaction, the condition for ignition is approximately six times more demanding (in confinement time or in plasma density) than the condition for breakeven.

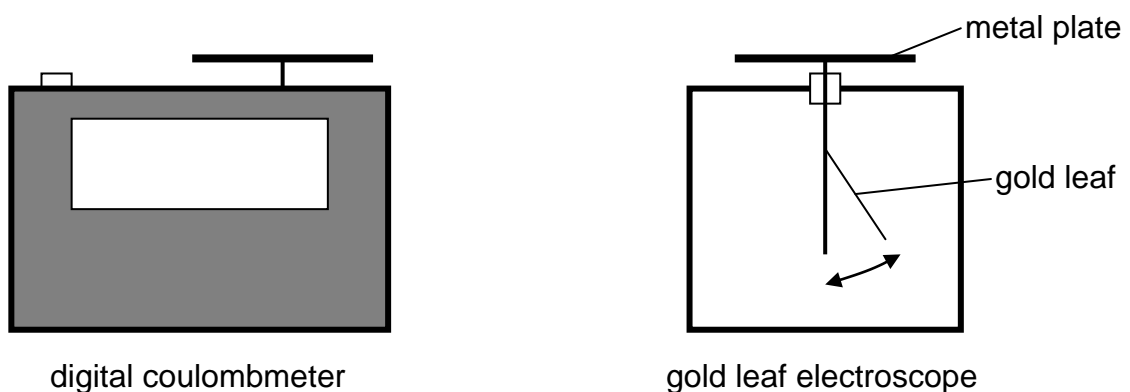
Wave-Particle Duality

The Photoelectric Effect

In 1887 Heinrich Hertz was experimenting with radio waves when he observed that the sparks at the receiver were much bigger when light from the large transmitter sparks was allowed to fall on the receiving spheres. Hertz did not follow this up, but others did. What Hertz had discovered was the photoelectric effect. This effect was first explained by Albert Einstein in a paper in 1905 for which he subsequently won the Nobel Prize for physics.

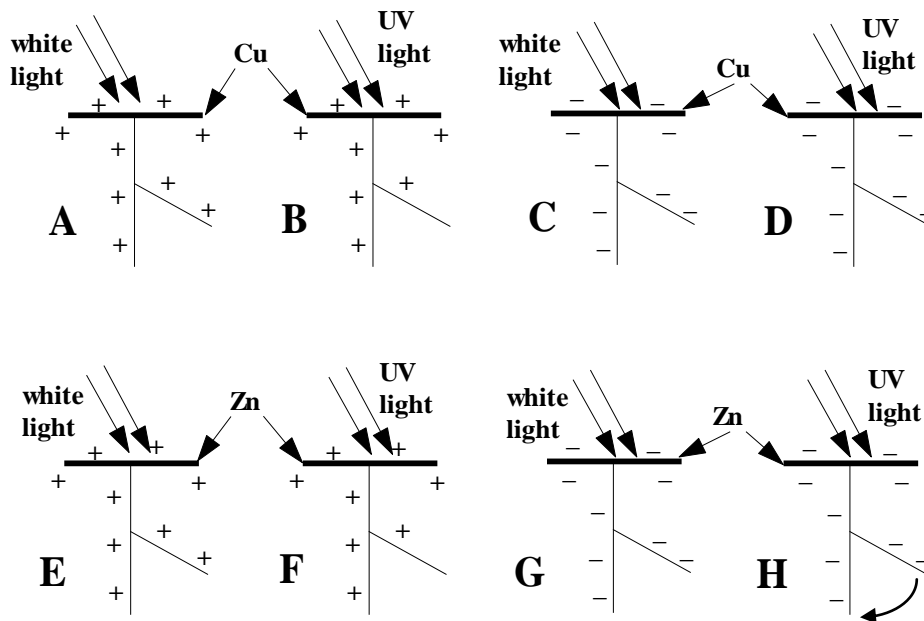


Under certain situations an electrically charged object can be made to discharge by shining electromagnetic radiation at it. This can be best demonstrated by charging a device on which the charge stored can be measured, either a digital coulombmeter or a gold leaf electroscope. As charge is added to a gold leaf electroscope the thin piece of gold leaf rises up at an angle from the vertical rod to which it is attached.



Different frequencies of electromagnetic radiation can be directed at different types of charged metals. The metals can be charged either positively or negatively.

In most circumstances nothing happens when the electromagnetic radiation strikes the charged metal, for example in situations A to G below. However, in a few cases, such as H below, a negatively charged metal can be made to discharge by certain high frequencies of electromagnetic radiation.



We can explain this **photoelectric effect** in terms of electrons within the zinc being given sufficient energy to come to the surface and be released from the surface of the zinc. The negative charge on the plate ensures that the electrons are then repelled away from the electroscope.

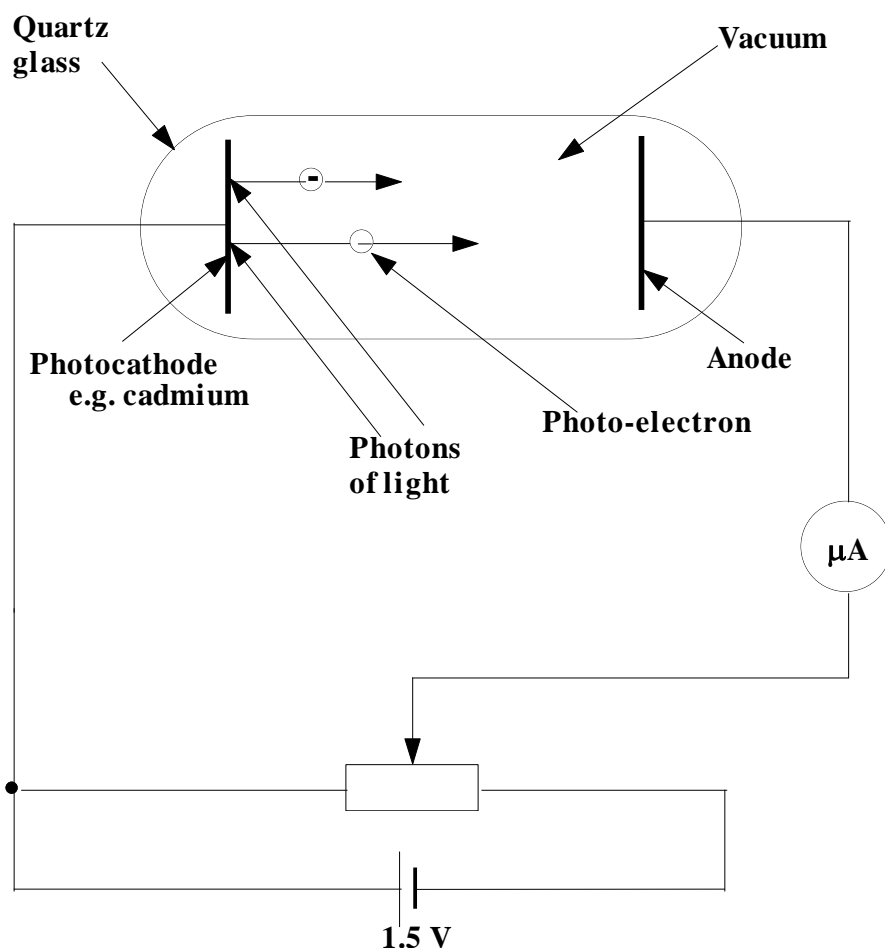
This cannot be explained by thinking of the light as a continuous wave. The light is behaving as if it were arriving in **discrete packets of energy** the value of which depends on the wavelength or **frequency** of the light. Einstein called these packets of energy **photons**.

The experimental evidence shows that photoelectrons are emitted from a metal surface when the metal surface is exposed to optical radiation of sufficient frequency. In case G any photoelectrons which are emitted from the zinc surface are immediately attracted back to the zinc metal because of the attracting positive charge on the electroscope. The electroscope does not therefore discharge.

It is important to realise that if the **frequency** of the incident radiation is **not high enough** then no matter how great the **irradiance** of the radiation **no** photoelectrons are emitted. This critical or **threshold frequency**, f_0 , is different for each metal. For copper the value of f_0 is even greater than that of the ultraviolet part of the spectrum as no photoelectrons are emitted for ultraviolet radiation. Some metals, such as selenium and cadmium, exhibit the photoelectric effect in the visible light region of the spectrum.

One reason why different metals have different values of f_0 is that energy is required to bring an electron to the metal surface and due to the different arrangements of atoms in different metals. Some metals will hold on to their electrons a little stronger than others. The name given to the small amount of energy required to bring an electron to the surface of a metal and free it from that metal is the **work function**. If measured in joules the value of this work function is very small, in the order of 10^{-19} or 10^{-20} J. This is comparable with the energy a single electron gains when it passes through a single 1.5 V cell.

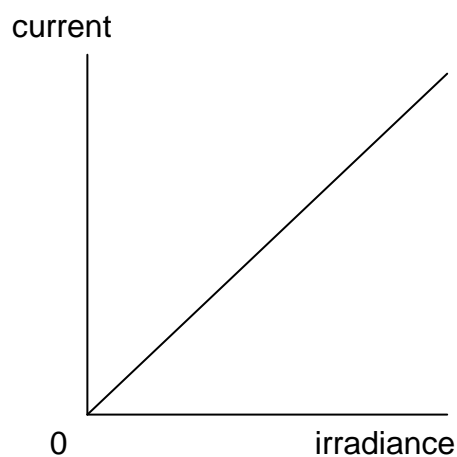
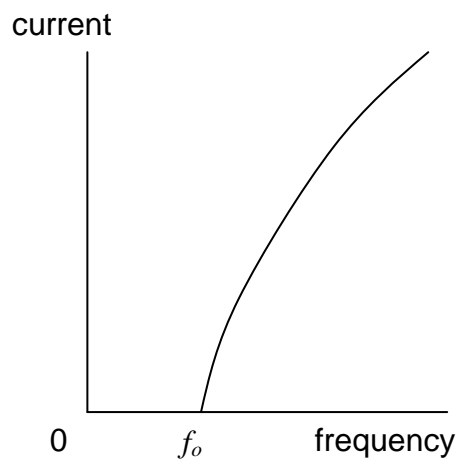
If a photon of incident radiation carries more energy than the work function value then the electron not only is freed at the surface but has "spare" kinetic energy and it can go places. An experiment can be carried out to demonstrate and quantify the photoelectric effect.



Notice that the supply is opposing the electron flow.

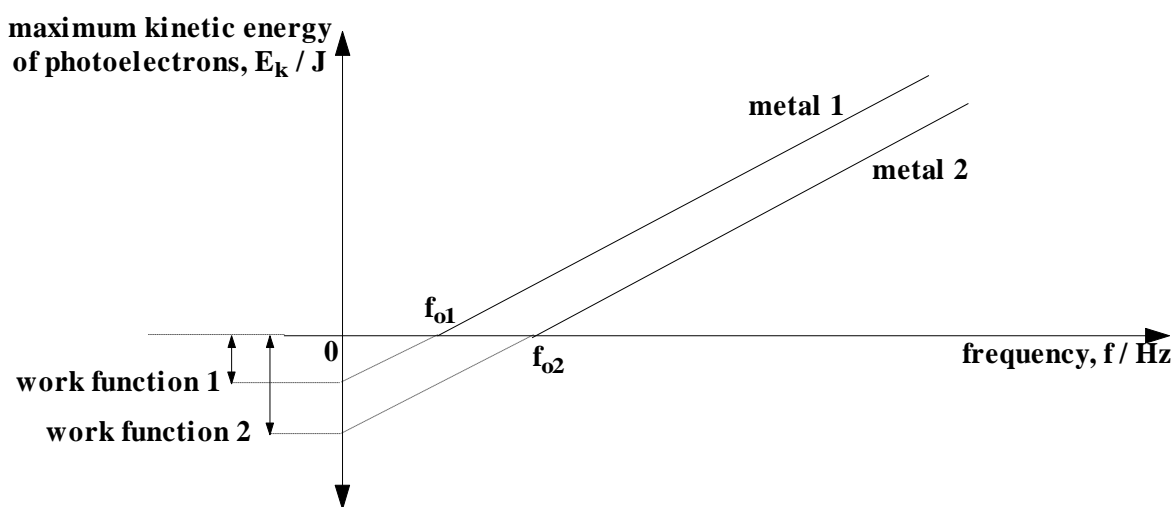
Initially with the supply p.d. set at 0 V, light of various wavelengths or frequencies is allowed to fall on the photocathode. In each case a small current is observed on the microammeter. The value of this current can be altered by altering the irradiance of the light as this will alter the number of photons falling on the cathode and thus the number of photoelectrons emitted from the cathode. In fact the photocurrent is directly proportional to the irradiance of the incident light - evidence that irradiance is related to the number of photons arriving on the surface.

If when red light only is used the p.d. of the supply is slowly turned up in such a direction to oppose the electron flow, there comes a point when the p.d. is just sufficient to stop all the photoelectrons from reaching the anode. This is called the stopping potential for red. The photoelectrons are just not reaching the anode as they have not sufficient kinetic energy to cross the gap to the anode against the electric field. In fact their kinetic energy has all been turned to potential energy and they have come to rest.



If the red light is now replaced with violet light, and no other alterations are made, a current suddenly appears on the microammeter. This means that some electrons are now managing to get across from the cathode to the anode. Hence they must have started out their journey with more kinetic energy than those produced by red light. This means that photons of violet light must be carrying more energy with them than the photons of red light. No matter how strong the red light source is or how weak the violet light source the photons of violet light always “win”.

If several experiments are done with photocells with different metal cathodes and in each case a range of different frequencies of light is used, graphs of maximum energy of photoelectrons against frequency of light can be plotted, as follows:



All metals are found to give straight line graphs which **do not** pass through the origin. However the gradient of each line is the same. This gradient is Planck’s constant h . The value of Planck’s constant is 6.63×10^{-34} Js. The work function of the metal is the intercept on the energy axis.

From the straight line graph it can be seen that:

$$y = mx + c$$

$$E_k = mf + c$$

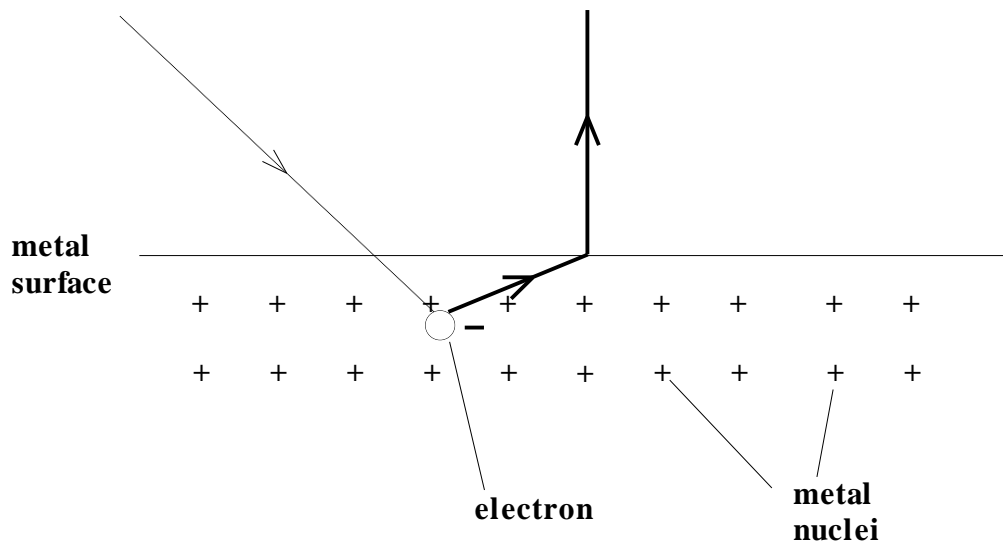
$$E_k = hf - W$$

Hence:

$$hf = W + E_k \quad \text{or} \quad hf = hf_o + E_k$$

energy of absorbed photon = work function + kinetic energy of emitted electron

In the following diagram label the three arrowed parts of the diagram, using the above descriptions and their respective formula parts.



We can calculate the energy of a typical visible light photon as follows:

The range of wavelengths in the visible spectrum is approximately 400 nm to 700 nm. Therefore an average wavelength from the visible spectrum is 550 nm.

- Calculate the frequency of this wavelength. (speed of light = $3.00 \times 10^8 \text{ m s}^{-1}$)

- Using $E = hf$, calculate the energy of the photon.

ELECTRON ARRANGEMENTS OF ELEMENTS

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 0
(1)	(2)	(13)	(14)	(15)	(16)	(17)	(18)

1 H Hydrogen	2 He Helium	3 Li Lithium	4 Be Beryllium	5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium	13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulphur	17 Cl Chlorine	18 Ar Argon	19 K Potassium	20 Ca Calcium
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium
55 Cs Cesium	56 Ba Barium	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium
87 Fr Francium	88 Ra Radium	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium
97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium
111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson	119 Uue Ununennium	120 Uub Unbibium

Key

Atomic number
Symbol
Electron arrangement
Name

TRANSITION ELEMENTS

(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc
39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium
57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium
101 Lu Lutetium	102 Hf Hafnium	103 Ta Tantalum	104 W Tungsten	105 Re Rhenium	106 Os Osmium	107 Ir Iridium	108 Pt Platinum	109 Au Gold	110 Hg Mercury
137 Fr Francium	138 Ra Radium	139 Ac Actinium	140 Th Thorium	141 Pa Protactinium	142 U Uranium	143 Np Neptunium	144 Pu Plutonium	145 Am Americium	146 Cm Curium
151 La Lanthanum	152 Ce Cerium	153 Pr Praseodymium	154 Nd Neodymium	155 Pm Promethium	156 Sm Samarium	157 Eu Europium	158 Gd Gadolinium	159 Tb Terbium	160 Dy Dysprosium
171 Lu Lutetium	172 Hf Hafnium	173 Ta Tantalum	174 W Tungsten	175 Re Rhenium	176 Os Osmium	177 Ir Iridium	178 Pt Platinum	179 Au Gold	180 Hg Mercury

LANTHANIDES

ACTINIDES

57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium