Airdrie Academy Physics Department

# *Particles*
# *And*
# *Waves*

# *Pupil Notes*

## Orders of magnitude

What are the extremes of scale from the size of the universe to the smallest particles we have found so far? 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 and so on. However, we do not experience the extremes of scale in everyday life so we have to 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. Numbers alone, however, can make it difficult to get a sense of how scale changes.

How many times bigger than you do you think the Earth is?

Follow what happens when we start from 1 metre and progress through seven orders of magnitude:

| | |
|---|---|
| 1 m | Human scale – the average British person is 1.69 m |
| 10 m | The height of a house |
| 100 m | The diameter of a city square, like George Square |
| $10^3$ m | The length of an average street |
| $10^4$ m | The diameter of a small city like Perth |
| $10^5$ m | Distance between Aberdeen and Aviemore or Stirling and Ayr |
| $10^6$ m | Length of Great Britain |
| $10^7$ m | Diameter of Earth |

As big as this jump is, you would need to do it nearly four times more to get to the edge of the universe! 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.

| Size | Powers of 10 | Examples |
|---|---|---|
| | $10^{-18}$ m | Size of an electron?<br>Size of a quark? |
| | $10^{-17}$ m | |
| | $10^{-16}$ m | |
| 1 fm (femto) | $10^{-15}$ m | Size of a proton |
| | $10^{-14}$ m | Atomic nucleus |
| | $10^{-13}$ m | |
| 1 pm (pico) | $10^{-12}$ m | |
| | $10^{-11}$ m | |
| 1Å (Angstrom) | $10^{-10}$ m | Atom |
| 1 nm (nano) | $10^{-9}$ m | Glucose |
| | $10^{-8}$ m | DNA<br>Antibody<br>Haemoglobin |
| | $10^{-7}$ m | Wavelength of visible light<br>Virus |
| 1 μm (micro) | $10^{-6}$ m | Lyosome |
| | $10^{-5}$ m | Red blood cell |
| | $10^{-4}$ m | Width of a human hair<br>Grain of salt |
| 1 mm (milli) | $10^{-3}$ m | Width of a credit card |
| 1 cm (centi) | $10^{-2}$ m | Diameter of a shirt button |
| | $10^{-1}$ 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 | Typical altitude of an airliner,<br>diameter of Large Hadron Collider, CERN |
| | $10^{5}$ m | Height of the atmosphere |

| | | |
|---|---|---|
| 1 Mm (mega) | $10^6$ m | Length of Great Britain |
| | $10^7$ m | Diameter of Earth<br>Coastline of Great Britain |
| | $10^8$ m | |
| 1 Gm (giga) | $10^9$ m | Moon's orbit around the Earth,<br>The farthest any person has travelled.<br>Diameter of the Sun. |
| | $10^{10}$ m | |
| | $10^{11}$ 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? |
| | $10^{14}$ m | |
| | $10^{15}$ m | |
| | $10^{16}$ m | Light year<br>Distance to Proxima Centauri, the next closest star |
| | $10^{17}$ m | |
| | $10^{18}$ m | |
| | $10^{19}$ m | |
| | $10^{20}$ m | |
| | $10^{21}$ m | Diameter of our galaxy |
| | $10^{22}$ m | |
| | $10^{23}$ m | Distance to the Andromeda galaxy |
| | $10^{24}$ m | |
| | $10^{25}$ m | |
| | $10^{26}$ m | |
| | $10^{27}$ m | Distance to the next galaxy cluster |
| | $10^{28}$ m | |
| | $10^{29}$ m | Distance to the edge of the observable universe |

http://commons.wikimedia.org/

**The fundamental questions – a story of particle physics**

Since ancient times, humans have asked fundamental questions. It seems to be part of our nature to seek to understand ourselves and our universe more fully.

- What are we made of?
- What is the world made of?
- Why do so many things in this world share the same characteristics?

This last question, in particular, led people to suspect that there must be some underlying structure. These fundamental building blocks were assumed to be simple and with no structure of their own. They were named **elements**. The Greeks had four (fire, air, earth and water), the Chinese five (earth, wood, metal, fire and water) and the Indians also five (space, air, fire, water and earth).

Another important question led to the idea of atoms: if you break a piece of matter in half, and then break it in half again, how many breaks will you have to make before you can break it no further? It was believed that this must end at some point, a smallest possible bit of matter. This concept was developed in ancient India, appearing first in Jainism. In the West, Democritus coined the term 'atom', which means indivisible ones, to describe these basic matter particles.

**Elements: the simplest chemicals**

These were purely philosophical concepts, essentially a matter of opinion. Experimental technology wouldn't be advanced enough to actually probe the structure of matter until the 18th century. In 1789 Antoine 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. However, estimates of the mass of some elements varied widely since science was yet to discover that some elements existed in diatomic form, i.e. two identical atoms joined together.

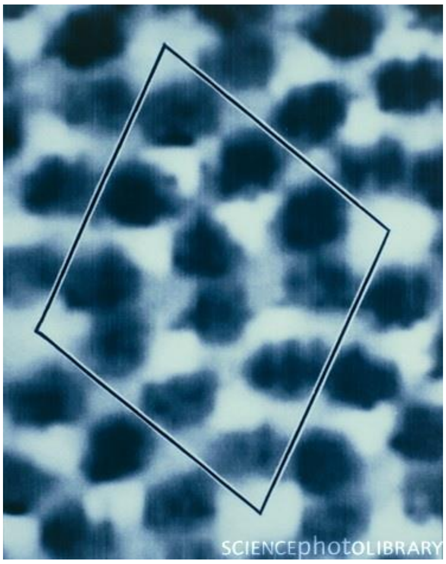
**The periodic table – order out of chaos**

In 1803 John Dalton measured very precisely the proportion of elements in various materials and reactions, and discovered that they always occurred in small integer multiples. This led him to resurrect the concept of atoms as the invisible and indivisible building blocks of everything. This is considered the start of modern atomic theory. In 1869 Mendeleev noticed that certain properties of chemical elements repeated themselves periodically when he organised them in the first periodic table.

**Atoms – indivisible?**

Has anyone actually seen an atom? No. All this evidence is secondary. We cannot actually see an atom no matter how much we magnify an image. To see something, we need to shine light on it and look at the reflections or shadows. The wavelength of light is significantly larger than the size of a single atom. This means that light will simply bend round individual atoms without any noticeable difference. In order for us to probe the structure of nature we need a different approach.

In 1897 J.J. Thomson discovered the electron and the concept of the atom as indivisible was gone, even though the word has stuck. However, this marked the birth of particle physics. In the long term it also led to the first images of the atom 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**

In 1909 Ernest Rutherford wanted to probe the structure of the atom itself. Electrons couldn't be used for this, since they simply bounce off the outside of the atoms. Instead he used newly discovered alpha particles to bombard a thin sheet of gold foil (or more correctly directed his students Geiger and Marsden to do so). By studying the pattern of how the alpha particles interacted with the gold atoms, he was able to form a picture of the atom with a positive nucleus and orbiting electrons called the Rutherford model. He also established the relative scale of the nucleus, at approximately 1/10,000th the size of the atom. This meant most of the atom was empty space.

At first it was thought that the nucleus was indivisible but the discovery of the neutron by James Chadwick in 1932 explained the existence of isotopes – the same element with the same number of protons but a different number of neutrons.

Science now had an elegant theory which explained the numerous elements. The classification and organisation of these elements around the properties that they shared (the periodic table) led to the revelation of an underlying structure. They were all constructed from combinations of three fundamental particles: electrons, protons and neutrons. However, if the atom, which had previously been considered fundamental, could be split, could these particles too?

**Subatomic particles**

Rutherford's idea of firing something at a target to discover its structure (if any) is known as scattering. He used alpha particles, since they were among the particles with the highest available energies at the time. However, over the coming decades scientists would develop and improve particle accelerators (or atom smashers as they are sometimes known) to enable them to probe deeper and deeper into the fundamental structure of matter. As these accelerators pushed back the bounds of technology, resulting in higher and higher energy, nearly 200 new particles were discovered, with exotic names like pions, muons and neutrinos. This is often known as the particle zoo because of the large numbers that were discovered, apparently with many different qualities and properties. However, as with the development of the periodic table, these particles were grouped together by their properties to reveal the possibility of underlying structure. Experimental evidence to support this theory came in the 1950s, when the scattering of high-energy electrons off nuclei by Hofstadter revealed some underlying patterns indicating that protons were not fundamental particles. However, this work did not conclusively identify the number and nature of the constituents of the protons.

**Antimatter**

These high-energy collisions also 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. Every particle of matter has a corresponding antiparticle. These were first proposed by Dirac in 1928, when he noticed that there were 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 in 1932 when they were discovered to be produced naturally from cosmic rays. This is the only antiparticle with a special name – it means ‘positive electron’.

**Quarks**

In 1964 Murray Gell-Mann and George Zweig both independently proposed that protons and neutrons consisted of three parts. Gell-Mann called these ‘quarks’ (pronounced kworks or kwarks). The particle zoo could now be reduced to a much more manageable number of fundamental particles. The standard model was developed to include these fundamental particles of matter and also to describe how they interact with each other. The first generation consisted of two quarks (called ‘up’ and ‘down’, and which can be combined to form neutrons and protons), the electron and the electron neutrino (which is produced during radioactive beta decay).

There are two more generations (each with four particles) and four bosons which are used to explain how most forces work. These 16 particles form our current understanding of matter (all other particles can be made from them) and most forces. Many were proposed theoretically years before being verified experimentally. Experimental evidence of the existence of quarks was provided by more detailed (deep inelastic) scattering experiments starting in 1968 at Stanford.

**What next?**

Given this success it may be tempting to think once again that physics has arrived at all the answers and that there is nothing more to do. However, there are many questions still waiting to be answered:

- Why is gravity so different from the other forces of nature? (The standard model does not include gravity.)
- Why do all electrons have the same mass?
- How do they know that is the mass they are meant to have? (The Higgs particle may help answer this question.)
- Why is it a matter universe, not an antimatter one?
- Why are there three generations of particles?

There are many more. Physics is alive and constantly pushing back the bounds of knowledge and technology.

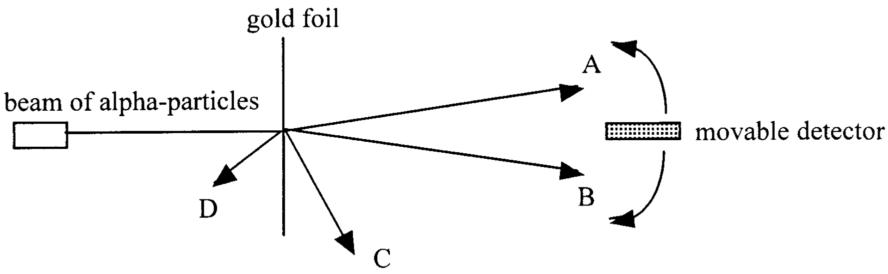
# The standard model of fundamental particles and interactions

## The Rutherford scattering experiment

Our theories of the structure of matter are not simply made up from the mind of physicists. They are grounded in experimental evidence and new theories, and then inform what the next experiment should be searching for. As experimental techniques improve, we can probe further and further into the structure of matter.

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.

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.



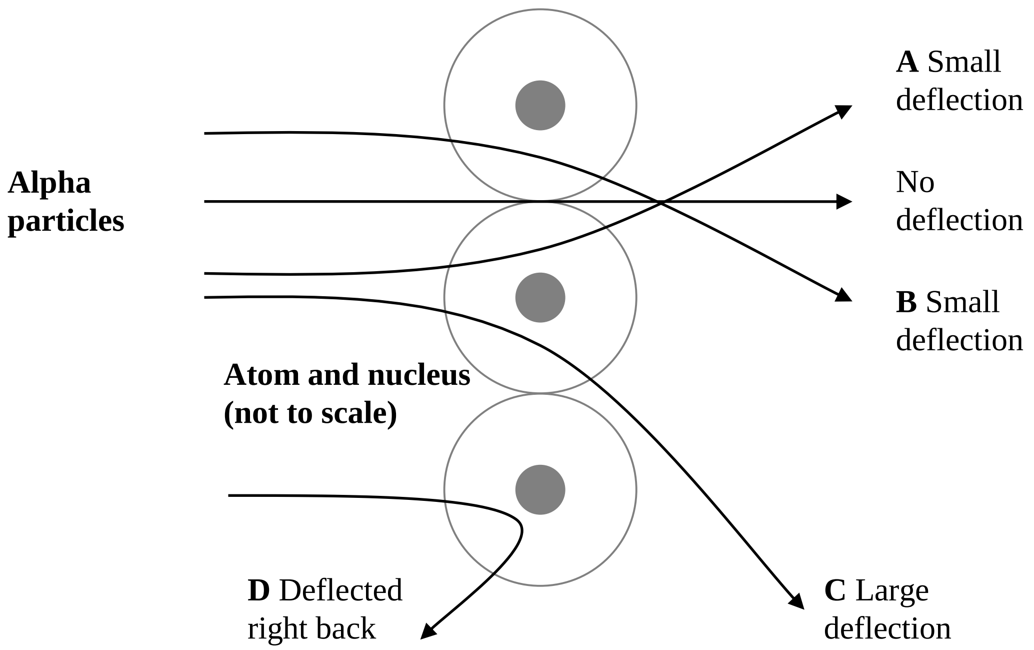

The main results of this experiment were:

- 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 was so surprised by this second result in particular that he described it as being like firing a cannonball at tissue paper and having it bounce back. It was known that the alpha particles were relatively heavy and fast moving, and if they were encountering the spread-out charge and matter of the Thomson model there would be nothing solid enough for them to bounce off. Thus the expectation was that all of the particles would be detected between A and B.

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 alpha particles must be encountering something of very large mass and a positive charge.




Rutherford suggested that the atom has a small positive nucleus, which contains most of the mass of the atom and is small compared to the size of the atom. The remaining space is taken up by the electrons (negative particles) orbiting the nucleus. By analysing the data he was able to estimate the diameter of the atom to be about 10,000 times the diameter of the nucleus.

As well as finding out a lot about the atom, Rutherford’s experiment became a template for future experimentation. Even though the technology has moved on considerably, the particle accelerators of today still have the same basic elements: beam, target and detector. You will learn more about particle accelerators later in this unit.

**The particle zoo**

The vast majority of ordinary matter is made up of protons, neutrons and electrons. However, in high-energy collisions many other particles can be created, most of which are very short-lived. From the 1930s to the 1990s nearly 200 such particles were discovered as the technology of particle accelerators improved (see http://pdg.lbl.gov/index.html for exhaustive lists). At first, many thought that each discovery was a new fundamental particle to add to the protons and electrons, which were already known about, and the newly discovered neutrons. Colloquially this was known as the particle zoo, with more and more new species being added. Attempts were made to organise the particles, the most successful theory being the eightfold way, which organised the new particles in groups of eight. This theory proposed the existence of previously unknown particles, and when these were discovered and shown to have the expected properties, the theory was shown to be useful.

In the 1950s Hofstadter revealed some underlying patterns in the scattering of high-energy electrons from nuclei. In the same way that the organisation of the periodic table can be explained in terms of protons, neutrons and electrons, scientists proposed that protons and neutrons were not fundamental themselves. In the 1960s the standard model proposed that only leptons could be considered fundamental but that the majority of them were made up from an even smaller family of elemental particles known as quarks. These quarks are never found in isolation but combine in pairs and triples to make up hadrons (a name meaning heavy ones that was coined in 1962 for particles similar to neutrons and protons).

**Standard model – matter**

The standard model represents our best understanding of the fundamental nature of matter. It proposes 12 fundamental particles, 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 electron charge ($1.6 \times 10^{-19}$ C).

| | First generation | Second generation | Third generation |
|---|---|---|---|
| **Quarks** | up (⅔) | charm (⅔) | top (⅔) |
| | down (–⅓) | strange (–⅓) | bottom (–⅓) |
| **Leptons** | electron (–1) | muon (–1) | tau (–1) |
| | (electron) neutrino (0) | muon neutrino (0) | Tau neutrino (0) |

The term ‘lepton’ (light ones) 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.

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

**Particle recipes**

Hadrons can be subdivided into baryons (which include protons, neutrons and particles heavier than these) and mesons (which are generally lighter than protons). According to the simple quark model of hadrons, each baryon and meson consists of a certain combination of quarks and antiquarks. An antiquark is identical to its corresponding quark but with the opposite charge. The combinations are as follows:

- Each baryon consists of three quarks.
- Each meson consists of a quark and an antiquark.

The charge on each hadron is simply equal to the sum of the charges of its constituent quarks and antiquarks. For example, the proton has a charge of +1, the neutron 0. The quark structure of these hadrons is thus:

| | | | |
|---|---|---|---|
| proton: | $p = u\ u\ d$ | neutron: | $n = u\ d\ d$ |
| | $p = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$ | | $n = \frac{2}{3} - \frac{1}{3} - \frac{1}{3}$ |
| | $p = 1$ | | $n = 0$ |

A negative pion ($\Pi^-$) has a charge of –1. The quark structure of this meson is thus:

negative pion: $\Pi^- = \bar{u}\ d$

$\Pi^- = -\frac{2}{3} - \frac{1}{3}$

$\Pi^- = -1$

Note that we never observe quarks in isolation, only in doubles or triples that give integer charge. Thus we never observe charges that are fractions of the electron charge. This means not every combination of quarks and antiquarks is possible. Using a bar above a quark means it is an antiquark e.g. ū.

**The standard model – 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 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 affect 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** | $10^{-18}$ | $10^{25}$ | $10^{-10}$ | Holding electrons in atoms |
| **Electromagnetic** | ∞ | $10^{36}$ | $10^{-20}$–$10^{-16}$ | Beta decay; decay of unstable hadrons |
| **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.

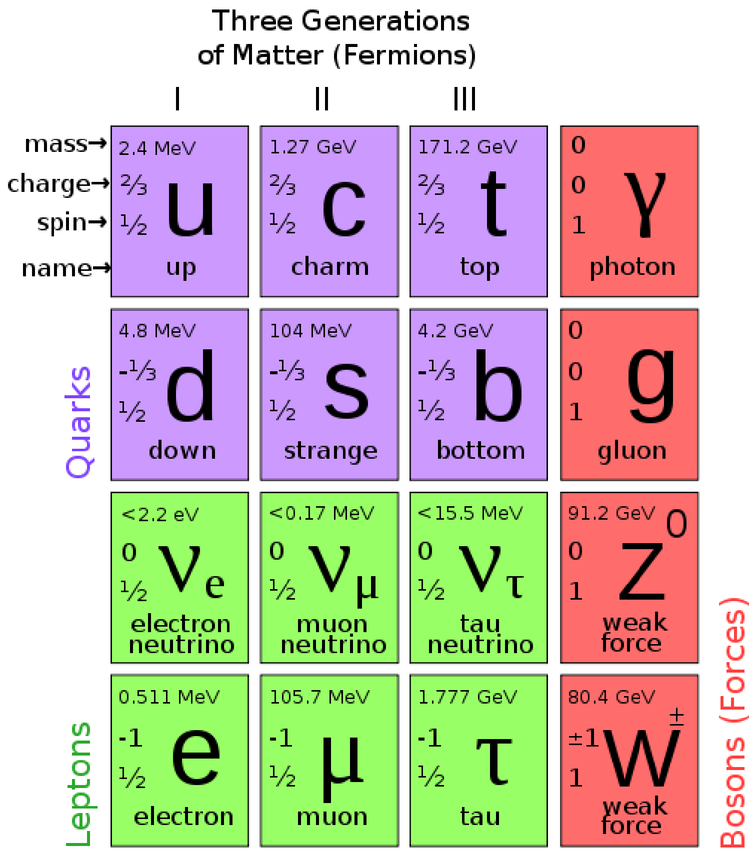
Consider a macroscopic analogy. The exchange particles for the four fundamental forces are given in the table below and most of these form part of the standard model. Much work has been done over the last century to find theories that combine these forces (just like Maxwell showed that the same equations 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 postulate the existence of a further boson, called the Higgs boson (sometimes referred to as the ‘God particle’), which isn’t involved in forces but is what gives particles mass. Attempts are being made to verify its existence experimentally using the Large Hadron Collider at CERN and the Tevatron at Fermilab.

**Standard model summary**



**Deep inelastic scattering**

There was still skepticism up to the 1960's within the scientific community about the standard model and experimental evidence was sought to validate and improve on this theory. Deep inelastic scattering is the name given to a series of experiments to do this through probing the structure of hadrons by firing high-energy particles at them.

The first breakthrough was performed in 1968 at Stanford Linear Accelerator, when electrons were accelerated to high speeds (and therefore high energy) and fired at protons. The electron was chosen as the beam particle since its charge made it easier to accelerate using electric fields and the combination with the positive proton meant that electrostatic attraction would also help. These electrons had an energy of 20 GeV, nearly 3000 times the energy of Rutherford's alpha particles. This made them more able to penetrate into the heart of the proton, hence the term 'deep'.

It was also found that kinetic energy was not conserved in these collisions, i.e. they were inelastic. (This 'missing' energy went into the creation of other particles that also emerged from the nucleus.)

The main findings were:

- Hadrons are not fundamental and have internal structure.
- Baryons have three points of deflection.
- Mesons have two points of deflection.
- Quarks appear to be fundamental, i.e. they act like single points.
- The fractional charge of the quarks agrees with the standard model.

Over many years similar experiments were performed with other beam particles and other hadron targets and were vital, firstly in proving the existence of another layer of fundamental particles and secondly proving that the standard model provided the best explanation among other competing theories. The evidence from such experiments was also used to further improve the standard model into the form we use today.

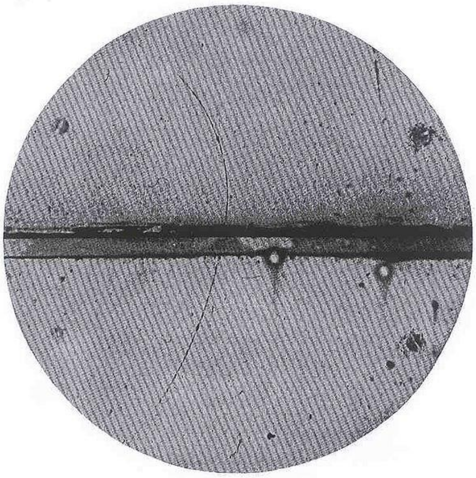
**Antimatter**

Antimatter is the name given to 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. Every particle of matter has a corresponding antiparticle.

Antimatter particles were first proposed by Dirac in 1928 when he noticed that there were 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. The particle was named the positron and experimental proof of its existence came in 1932 when positrons were discovered by Anderson to be produced naturally from cosmic rays. This is the only antiparticle with a special name (meaning positive electron). It is often given the symbol $e^+$. Other antiparticles are simply symbolised by a bar above their normal symbol, e.g. $\bar{u}$ is the antiparticle of the up quark.

The experimental proof for the positron came in the form of tracks left in a cloud chamber. This is a photograph of the first positron ever identified:



The tracks of positrons were identical to those left by electrons but curved in the opposite direction. You will learn more about cloud chambers and other particle detectors later in this unit.

**Annihilation**

Annihilation occurs when a particle meets its antiparticle and both particles disappear. At low energies this results in the production of a pair of photons, i.e. the combined mass/energy of the particles disappears and is replaced by pure energy. Conservation of energy and momentum mean that it is always at least a pair of photons that is produced. At higher energies more than two photons and various other heavy particles may be produced. Many of the new particles discovered in the 20th century were identified from deliberate annihilation experiments. The top quark was one such particle, the existence of which was confirmed at Stanford in 1992 in a collision of energy 176 GeV.

Antimatter is also created naturally in radioactive beta decay.

**What next for antimatter?**

In 1995 CERN became the first laboratory to create antiatoms artificially. This was done by combining an antiproton and a positron to make antihydrogen. Since this is not charged, containment was a big issue as most antimatter is contained using magnetic fields to cause the particle to stay confined to a circle. These experiments are being done to try and answer one of the fundamental questions:

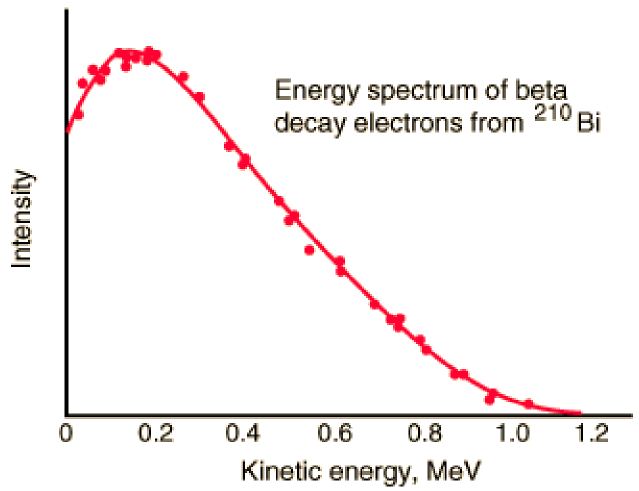
- Why is our universe a matter universe?
- Where is all the antimatter?

It is hoped that we can answer these questions by understanding the differences and similarities between matter and antimatter. We know that when we create antimatter we always create the corresponding matter particle in what is known as pair production. There is an apparent symmetry in the creation of matter and antimatter. However when we observe the universe today there appears to be more mater than antimatter. There are lots of theories to explain this matter imbalance that can be tested:

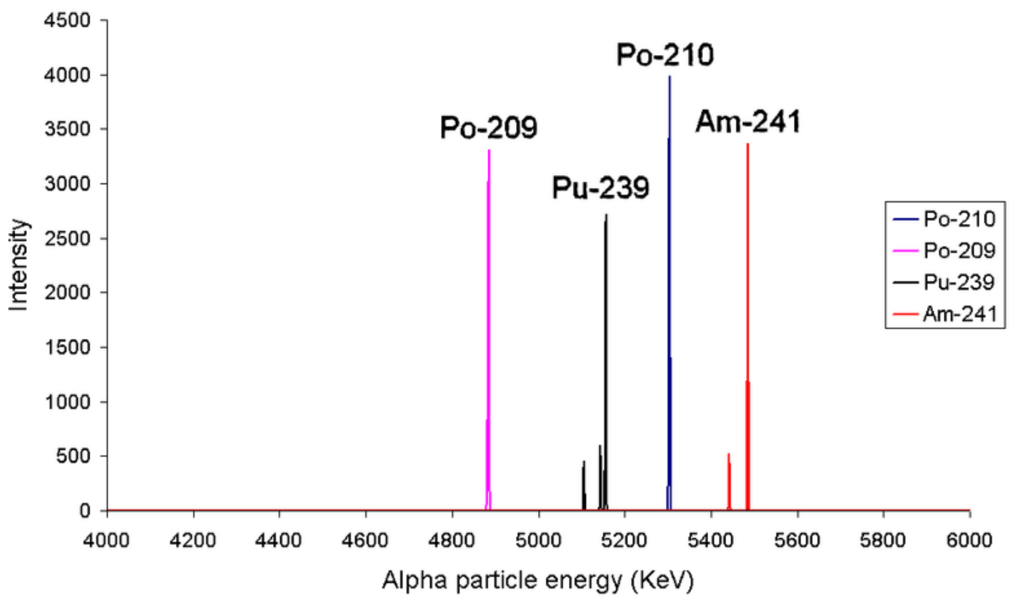
- Were the rules of pair production different at the time of the big bang?
- Did something prevent annihilation?
- Does the antimatter exist somewhere in the universe? (All evidence so far indicates not.)
- Is there a separate antiuniverse?

**Beta decay and the antineutrino**

Antimatter can also be produced in radioactive decay. You may already know that beta decay produces an electron, but how can a nucleus emit an electron when there are no electrons in the nucleus? The answer involves the weak nuclear force and antimatter. In beta decay a neutron 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. Only the weak force can cause such a change in flavour, i.e. from one type of quark to another. The electron is forced out at high speed due to the nuclear forces. This carries away kinetic energy. However, precise measurement of this energy has shown that there is a continuous spread of possible values, something that was unexpected.




The reason this was unexpected was that alpha radiation came out with a set of distinct energies rather than a continuous spread:




For example Pa-231 (protactinium) emits alpha particles with nine distinct energies. These separate energies could be calculated from the difference in the energy of the emitting nucleus before and after the decay process. The electrons in beta decay come out with a range of energies up to but not including the expected value. Something was needed to account for the missing energy and momentum. Pauli proposed in 1931 that there must be a second particle emitted in the decay. Since this had not been detected it would have to be neutral and highly penetrating, meaning it did not interact with the detectors. It was later named as a neutrino, but we now know that it is an antineutrino.

There is also another type of beta decay, known as $\beta^+$, which has a certain symmetry with the $\beta^-$ decay above. In this process a proton decays into a neutron, and a positron and neutrino are emitted.

**Interesting facts**

More than 50 trillion solar neutrinos pass through an average human body every second while having no measurable effect. They are so penetrating that to detect them requires massive tanks of water solution and photomultipliers to detect light produced by the interaction with the chemicals in the solution. These tanks are usually buried deep underground to prevent interference from other particles.

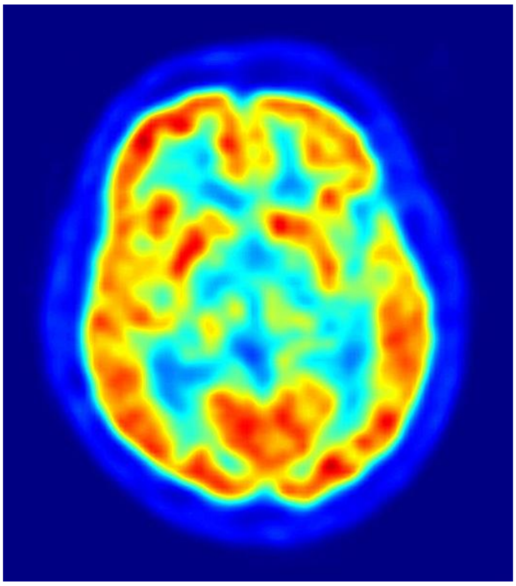
Pauli suggested the neutrino be called a neutron – the particle we now call the neutron would not be discovered for another year and Chadwick seemed unaware of Pauli's suggestion. Fermi suggested the name neutrino, which is Italian for small neutral one, to distinguish between the two.

**Positron emission tomography**

Positron emission tomography (PET) uses antimatter annihilation to obtain detailed 3-D scans of body function. CT and MRI scans 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 $\beta^+$ 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 in a ring of scintillations, 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.



© Jens Langner

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.

## Particles and waves

In this section we will explore the idea of the force field in physics, in relation to electric charge.

Having studied electricity at a lower level level, you may feel confident that you have a good grasp of the concepts surrounding electricity. Rest assured there will be new challenges in this section of work. Like many areas of physics, we build our understanding in a spiral – revisiting previous topics and building on them to extend our conceptual understanding, and explaining this verbally, graphically, mathematically, visually and in writing.

Lord Kelvin (1824–1907) recognised the challenges associated with scientific understanding:

> But when I think how infinitely little is all that I have done I cannot feel pride; I only see the great kindness of my scientific comrades, and of all my friends in crediting me for so much. One word characterises the most strenuous of the efforts for the advancement of science that I have made perseveringly during fifty-five years; that word is failure. I know no more of electric and magnetic force, or of the relation between ether, electricity, and ponderable matter, or of chemical affinity, than I knew and tried to teach to my students of natural philosophy fifty years ago in my first session as Professor. Something of sadness must come of failure; but in the pursuit of science, inborn necessity to make the effort brings with it much of the *certaminis gaudia*, and saves the naturalist from being wholly miserable, perhaps even allows him to be fairly happy in his daily work. And what splendid compensation for philosophical failures we have had in the admirable discoveries by observation and experiment on the properties of matter, and in the exquisitely beneficent applications of science to the use of mankind with which these fifty years have so abounded!

Lord Kelvin (William Thomson), Professor of Natural Philosophy, University of Glasgow (1846–1899) on the occasion of Lord Kelvin's 50-year jubilee as a professor.

Michael Faraday (1791–1867) noted:

> The cases of action at a distance are becoming, in a physical point of view, daily more and more important. Sound, light, electricity, magnetism, gravitation, present them as a series. The nature of sound and its dependence on a medium we think we understand, pretty well. The nature of light as dependent on a medium is now very largely

> accepted. The presence of a medium in the phenomena of electricity and magnetism becomes more and more probable daily. We employ ourselves, and I think rightly, in endeavouring to elucidate the physical exercise of these forces, or their sets of antecedents and consequents, and surely no one can find fault with the labours which eminent men have entered upon in respect of light, or into which they may enter as regards electricity and magnetism. Then what is there about gravitation that should exclude it from consideration also? Newton did not shut out the physical view, but had evidently thought deeply of it; and if he thought of it, why should not we, in these advanced days, do so too?

Letter to E Jones, 9 June 1857. In: L Pearce Williams (ed.), *The Selected Correspondence of Michael Faraday* (1971), Vol. 2, 870–1Cambridge University Press.

The first questions to consider are:

- What do you know about electricity?
- What do you know about the standard model of the atom?

Create a mind map or other summary which you can add to as you progress through this section and the later section on Electrons at work.

### Electric charge

Electric charge is given the symbol $Q$ and is measured in coulombs (C). In an electrical circuit, the charge carriers are electrons, which flow from negative to positive. You should be able to explain, in terms of simple electrostatics, why the electrons flow from negative to positive.

Note that other countries, and information you find in books and on the web, may use the term ‘conventional current’. In this situation, the charge carriers are considered to be positive, and to flow from positive to negative.

The charge on a proton is $1.6 \times 10^{-19}$ C. The charge on an electron? It is the same magnitude but opposite in sign, i.e. $-1.6 \times 10^{-19}$ C.

Recall that when like charges (i.e. positive and positive, or negative and negative) are brought together, they repel one another. When opposite charges (i.e. positive and negative) are brought together, they attract one another.

For the charges to experience a change in motion, they must experience an unbalanced force.

**Magnetic fields**

In physics, a field means a region where an object experiences a force without being touched. For example, there is a gravitational field around the Earth. This attracts mass towards the Earth's centre. Magnets are surrounded by magnetic fields and electric charges by electric fields.

Check your knowledge of magnetic fields by sketching the shape of the magnetic field around a bar magnet.

**Electric fields**

In an electric field, a charged particle will experience a force. The electric field surrounding a point charge or parallel plates can be demonstrated using a high-voltage power supply connected to electrodes dipped in a Petri dish and some small seeds in oil. A Van de Graaff generator can be used to demonstrate that the electric field extends in all directions from the charge.

The electric field shape for two point sources, one positive and one negative, is:

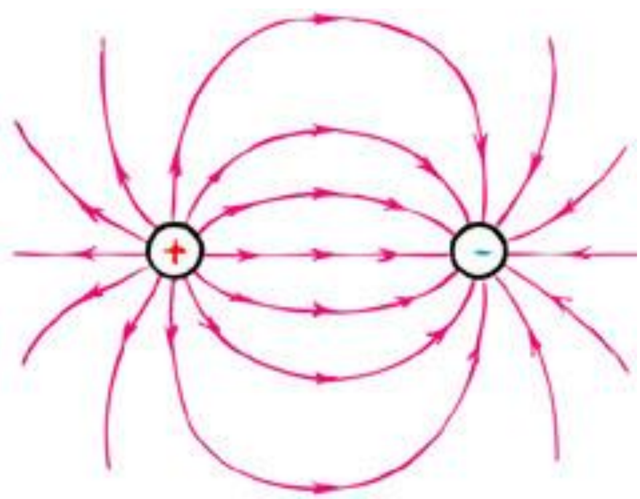



Image: http://facstaff.gpc.edu/~pgore/PhysicalScience/electric-charge.html.

Compare this with the magnetic field around a bar magnet:

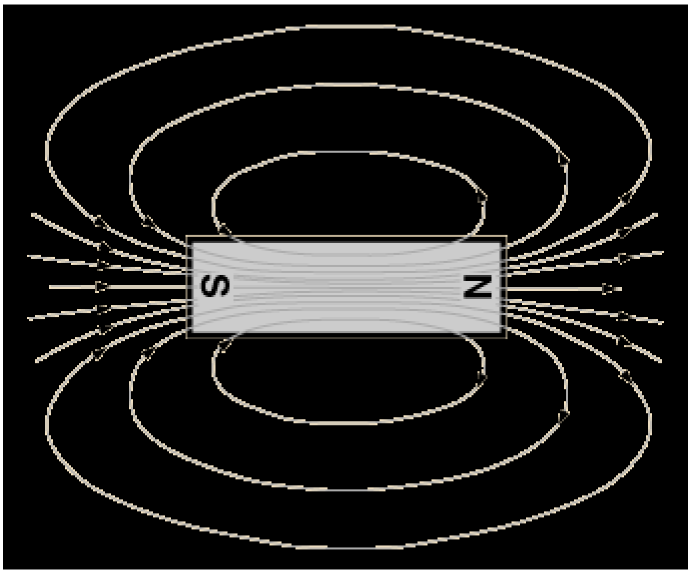
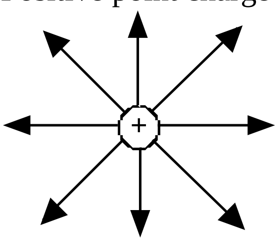



Image: Hyperphysics, Department of Physics and Astronomy, Georgia State University (Author C.R. Nave)

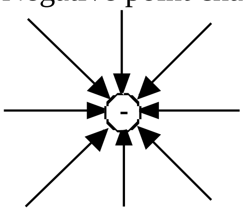
Other electric field patterns are shown:

Positive point charge




Positive test charge experiences a force ‘outwards’

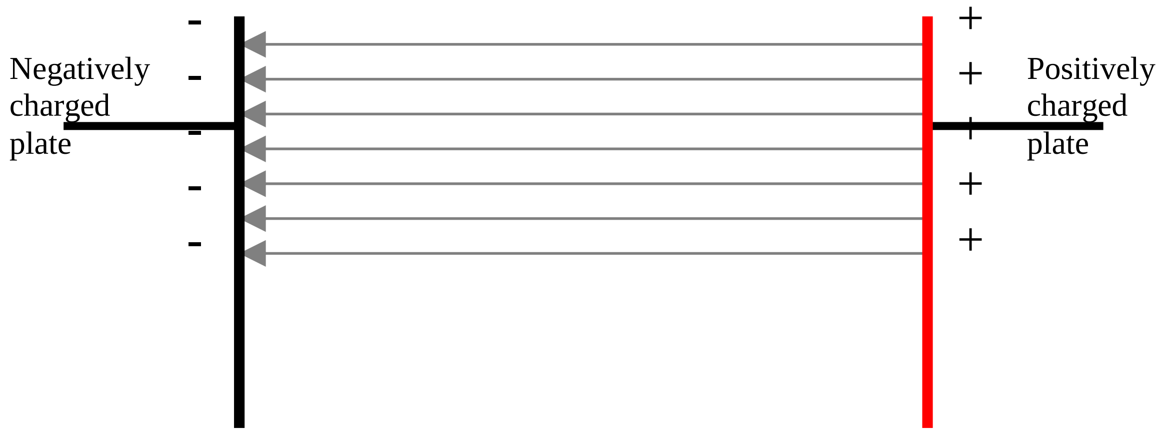
Negative point charge




Positive test charge experiences a force ‘inwards’

These are called 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 a gravitational field.

The electric field pattern for parallel plates is:




The electric field is represented by field lines. Looking at the diagrams, what information can we obtain from the field lines?

The electric field lines give us information on:

- the direction in which a force will act
- the direction in which a positive charge will move, shown by the arrows on the field lines
- the strength of the field, shown by the spacing of the field lines – the closer together the lines, the stronger the field.

Electric fields play an important role in everyday life. Investigate and discuss examples, including:

- the cathode ray tube (the basis for traditional television and monitor systems)
- paint spraying, e.g. for cars
- photocopying and laser printing
- pollution control.

Electric fields can also cause problems, for example during lightning storms there is a risk of damage to microchips within electronic devices caused by static electricity.

**Using gravitational fields to help understand electric fields**

If you have already studied Our Dynamic Universe, you will have an understanding of gravitational force.

**Describe the motion of a tennis ball released from a height under the force of gravity**

Air resistance is negligible.

Is the acceleration constant or changing? From this, conclude whether the gravitational field is a uniform or a varying field.

When the tennis ball is released in the gravitational field, a force is exerted on it. The force acts in the direction of the gravitational field. We recall that the force of gravity is always attractive, acting towards the centre of the mass. The ball will accelerate downwards. The acceleration is constant. The unbalanced force must therefore be constant. The gravitational field must be a uniform field.

**Describe what happens to the energy of an object raised in a gravitational field**

Work must be done to raise the object against the direction of force. When held at a height, i.e. when moved from its natural position, there is energy stored in the field–ball system, i.e. the gravitational field is a potential store of energy. When the ball is released there is a mechanical transfer of energy to a kinetic store of energy, i.e. the ball will move.

Recall the relationships:

$E_w = Fs$

$E_w$ is energy (work done) in joules (J)
$F$ is force in Newtons (N)
$s$ is displacement (m)

$E_p = mgh$

$E_p$ is energy in joules (J)
$m$ is the mass measured in kilograms (kg)
$g$ is the gravitational field strength in Newtons per kilogram (N $kg^{-1}$)
$h$ is the height measured in metres (m)

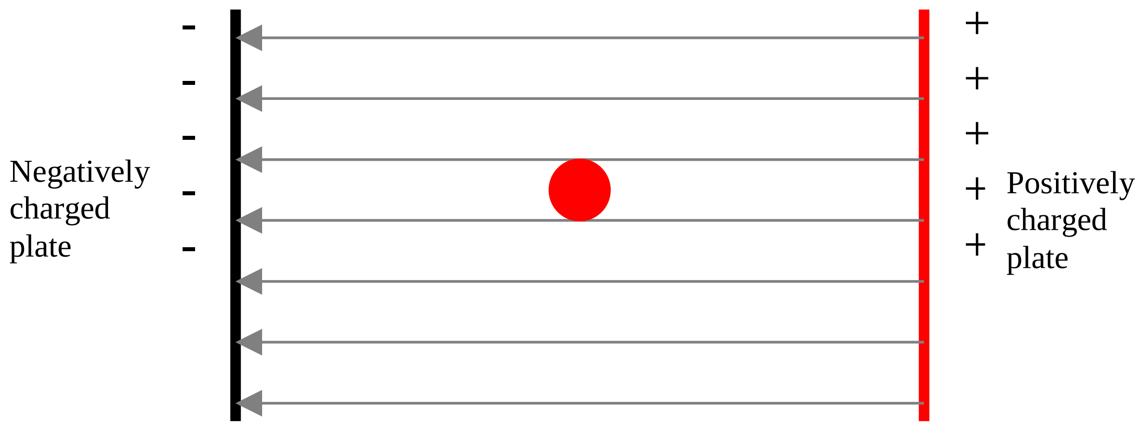
$E_k = \frac{1}{2}mv^2$

$E_k$ is energy in joules (J)
$m$ is the mass measured in kilograms (kg)
$v$ is speed measured in metres per second (m $s^{-1}$)

**Conservation of energy** allows us to equate these relationships in the absence of air resistance:

$$E_w = E_p = E_k$$
$$Fs = mgh = \tfrac{1}{2}mv^2$$

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




Describe the motion of this particle when released.

When the small positive charge is released between the parallel plates a force is exerted on it. The force acts in the direction of the electric field. We recall that like charges repel and opposite charges attract. The small positive charge will accelerate 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.

Notice in this description the link between the motion of a small positive charge in an electric field and a tennis ball in a gravitational field.

Next, 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. When the ball is released there is a transfer of energy to a kinetic store of energy, i.e. the charge will move.

Using conservation of energy we can equate these energies, i.e.

work done = change in electric potential energy

The potential difference between two points is defined to be a measure of the work done in moving one coulomb of charge between two points in an electric field.

Your teacher may discuss analogies to help you improve your understanding of the concept of potential difference. It is commonly also called voltage.
This relationship can be written mathematically:

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

$E_w$ is energy (work done) in joules (J)

$Q$ is the charge in coulombs (C)

$V$ is the potential difference (pd) in volts (V)

This gives us a definition for the volt: 1 volt is the potential difference between two points in an electric field where 1 joule of energy is required to move 1 coulomb of charge between those two points, i.e. 1 volt is equivalent to 1 joule per coulomb. (1 V = 1 $JC^{-1}$).

$$E_w = QV$$

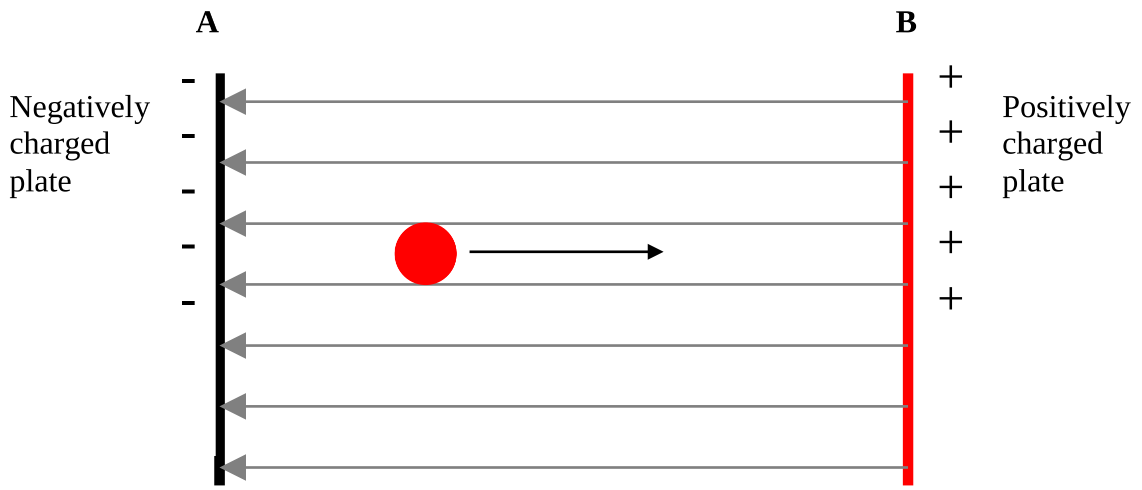
$E_w$ is energy (work done) in joules (J)

$Q$ is the charge in coulombs (C)

$V$ is the potential difference (pd) in volts (V)

**Example**

A positive charge of 3 µC is moved from A to B. The potential difference between A and B is 10 V.




(a) Calculate the electric potential energy gained by the charge–field system.

(b) The charge is released. Describe its motion.

(c) Determine the kinetic energy when the charge is at point A.

(a)

$E_w = QV$
$E_w = 3 \times 10^{-6} \times 10$
$E_w = 3 \times 10^{-5}$ J

$E_w$ is energy (work done) in joules (J)

$Q = 3 \times 10^{-6}$ C

$V = 10$ V

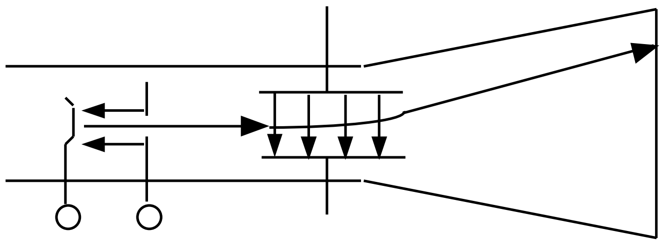
(b) The field is uniform so the charge will experience a constant unbalanced force. It will accelerate uniformly towards the negative plate A.

(c) By conservation of energy, $3 \times 10^{-5}$ J.

The solution to part (c) shows that we can use the conservation of energy to equate the work done with the kinetic energy, in the same way as we can when dealing with objects in gravitational fields.

**Moving charged particles in electric fields: useful applications**

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 to late 2000s. The cathode ray tube continues to be the basis for scientific equipment such as the oscilloscope and military radar systems. In the mid 1960s the University of Illinois, recognising the problems using cathode ray tubes as computer displays (problems such as poor resolution and low refresh rate), began the development of plasma televisions. Work on liquid crystals also began in the 1960s, but it was 1997 before Hitachi produced the world's first liquid crystal display (LCD) of a standard that could be used in a television. CRT displays are still favoured in many high-end broadcast and printing applications due to superior colour balance.



From the example on page 11, by conservation of energy:

$$QV = \tfrac{1}{2}mv^2$$

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:

(a) the kinetic energy, $E_k$, of the electron
(b) the final speed of the electron.

$E_k = \tfrac{1}{2}mv^2 = QV$

$E_w = 1.6 \times 10^{-19} \times 200$

$E_w = 3.2 \times 10^{-17}$ J

$E_w$ is energy (work done) in joules (J) = $E_k$

$Q = -1.6 \times 10^{-19}$ C

$V = 200$ V

$m = 9.1 \times 10^{-31}$ kg

$v = ?$ m s$^{-1}$

$\frac{1}{2}mv_2 = 3.2 \times 10^{-17}$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = 3.2 \times 10^{-17}$

$$v^2 = \frac{3.2 \times 10^{-17}}{\frac{1}{2} \times 9.1 \times 10^{-31}}$$

$v = 8.4 \times 10^6$ m s$^{-1}$

$E_w$ is energy (work done) in joules (J) = $E_k$

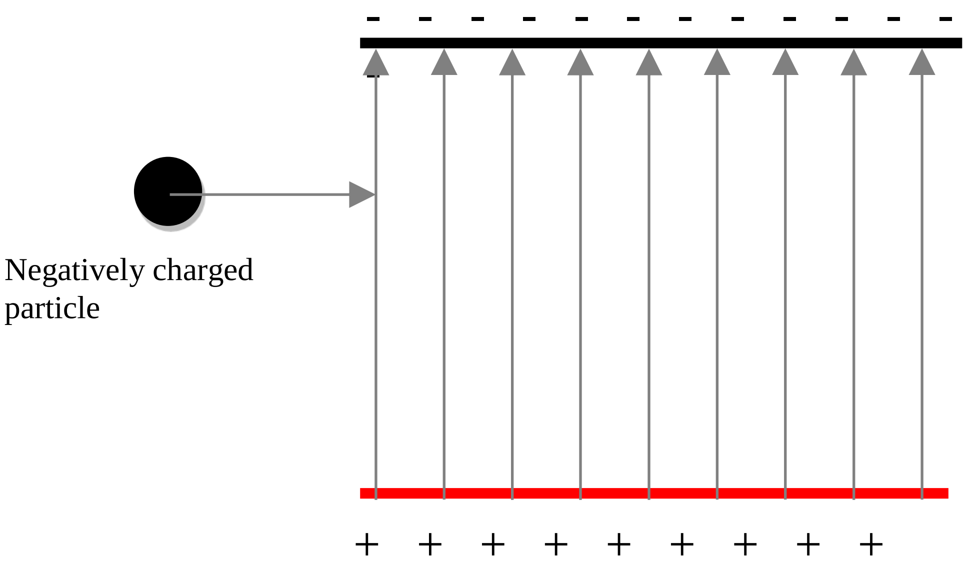
$Q$ = -1.6 × $10^{-19}$ C

$V$ = 200 V

$m$ = 9.1 × $10^{-31}$ kg

$v$ = ? m s$^{-1}$

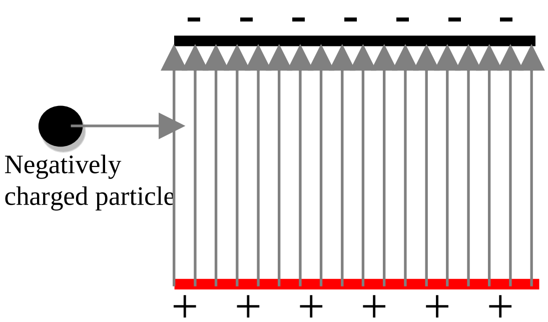
**Check your understanding**

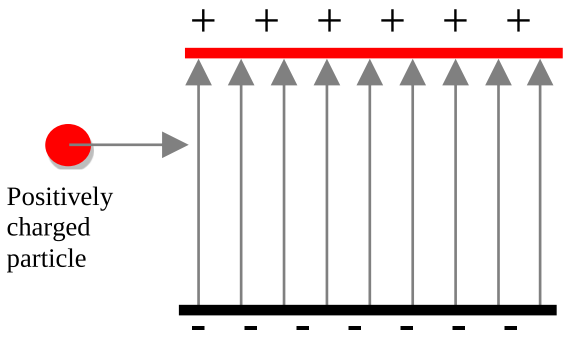



(a) Describe the motion of the negatively charged particle as it passes between the plates.

(b) Explain the motion of the negatively charged particle as it passes between the plates.

(c) Describe and explain the motion for each of the following situations:






Where have you come across this type of motion before?

## Charged particles and magnetic fields

What is the most important discovery or invention in history?

There are many possible answers to this question, but 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 impact on everyday life.

This work was carried out by Michael Faraday (1791–1867), whose work on electromagnetic rotation in 1821 gave us the electric motor. He was also instrumental in the work which brought electricity into everyday life, with the discovery of the principle of the transformer and generator in 1831.

However, 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!’ In fact it was more than 150 years later that this prediction of Faraday became true.

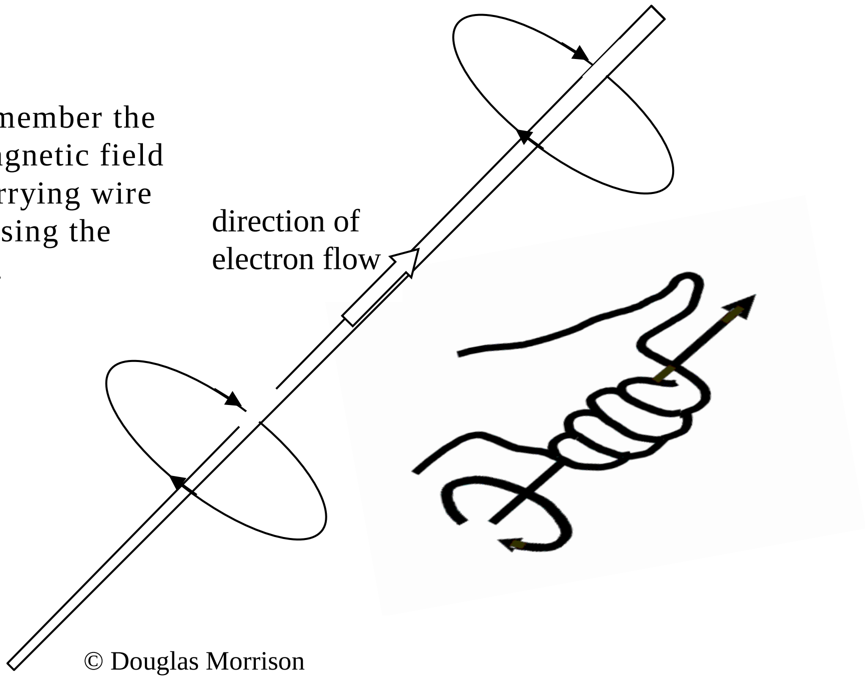
In the last section we explored the electric field that surrounds a stationary electric charge.

Questions to consider and discuss:

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

When a charged particle moves a magnetic field is generated. A current-carrying wire will have a magnetic field around it. This can be demonstrated with simple experiments. It is also possible to investigate the shape of this magnetic field, as well as how to increase, decrease and change the direction of the field.

It is possible to remember the direction of the magnetic field round a current-carrying wire for electron flow using the left-hand grip rule.



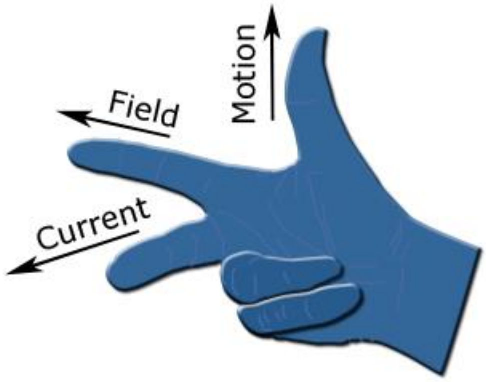

The electric field surrounding a stationary charged particle and the magnetic field surrounding a moving charged particle are not two entirely separate fields. The work of James Clark Maxwell (1831–1879), an Edinburgh-based scientist, identified the theory of electromagnetism and the equations describing the interaction between electric and magnetic fields.

What happens when two magnetic fields interact? Consider a simple case, e.g. bringing two bar magnets together. The magnets will each attract or repel due to an interaction between the magnetic fields surrounding each of the magnets.

So, what will happen when a moving electric charge is brought into a static magnetic field? The moving electric charge is surrounded by a magnetic (electromagnetic) field, which will interact with the static magnetic field or with any other magnetic or electromagnetic field. The moving electric charge will therefore experience a force. This can be compared to an object with mass experiencing a force when in a gravitational field.

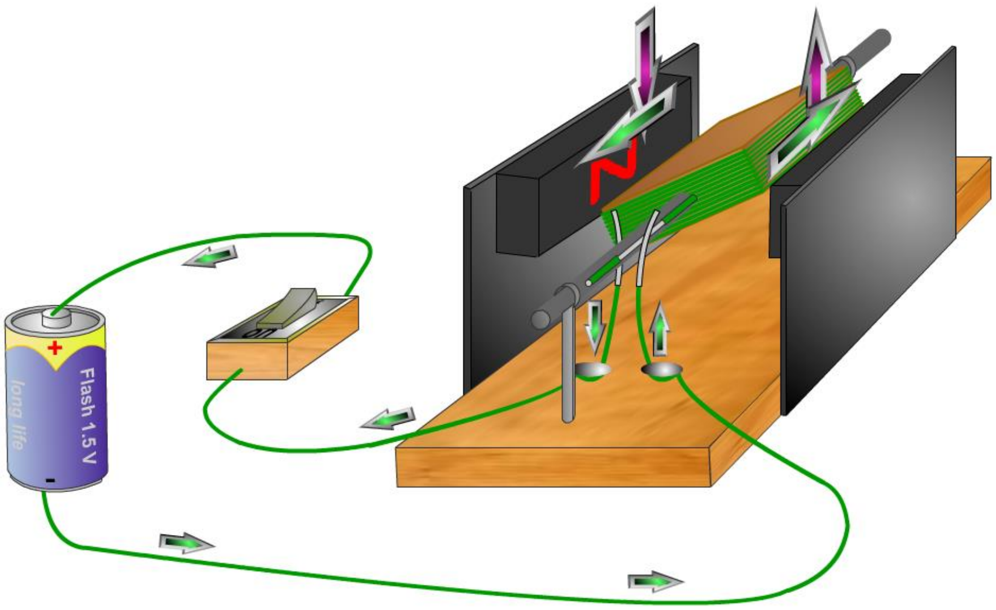
Simple rules can be used to determine the direction of force on a charged particle in a magnetic field.

For **electron flow**, the **right-hand motor** rule applies:



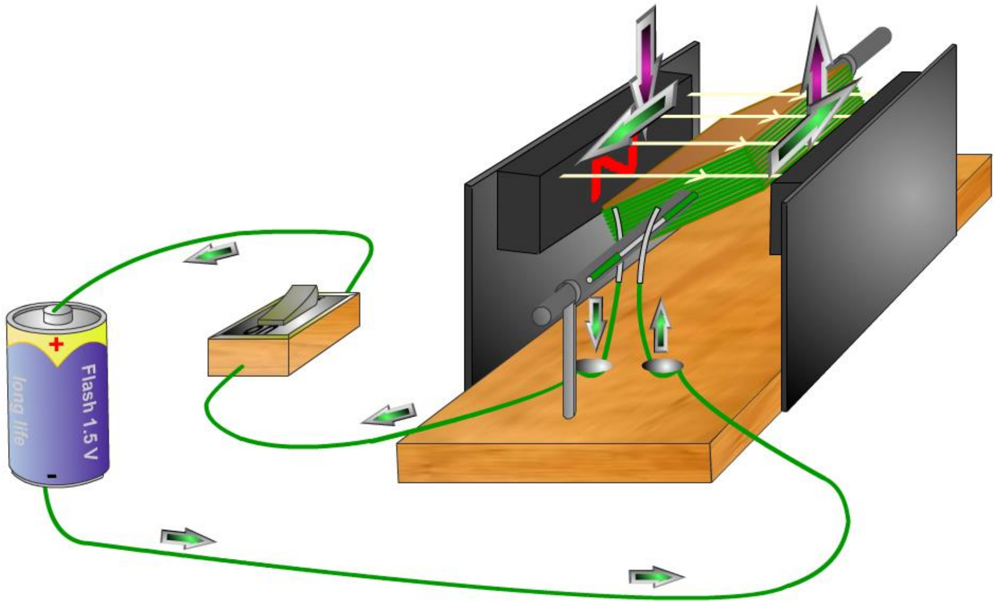

© Douglas Morrison.

The following images show how the right-hand motor rule (for electron flow) works for a motor (images courtesy of www.flashlearning.co.uk):

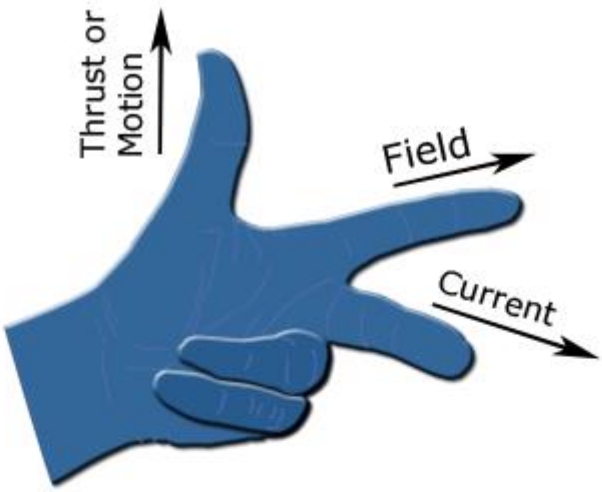



In the image above, from the current flow marked in green and the direction of unbalanced force (and therefore motion) in purple, predict the direction of the magnetic field.

Check your prediction in the image below. The field is marked in cream.




For **conventional current** (i.e. a flow of positive charge) the **left-hand motor rule** applies:




© Douglas Morrison.

## Particle accelerators

The Large Hadron Collider (LHC) at CERN (Conseil Européen pour la Recherche Nucléaire) is possibly the best-known particle accelerator in the world.

### ‘Our understanding of the universe is about to change…’

The Large Hadron Collider (LHC) is a gigantic scientific instrument near Geneva, where it spans the border between Switzerland and France about 100 m underground. It is a particle accelerator used by physicists to study the smallest known particles – the fundamental building blocks of all things. It will revolutionise our understanding, from the minuscule world deep within atoms to the vastness of the universe.

Two beams of subatomic particles called ‘hadrons’ – either protons or lead ions – will travel in opposite directions inside the circular accelerator, gaining energy with every lap. Physicists will use the LHC to recreate the conditions just after the Big Bang, by colliding the two beams head-on at very high energy. Teams of physicists from around the world will analyse the particles created in the collisions using special detectors in a number of experiments dedicated to the LHC.

There are many theories as to what will result from these collisions. A brave new world of physics will emerge from the new accelerator, as knowledge in particle physics goes on to describe the workings of the universe. For decades, the standard model of particle physics has served physicists well as a means of understanding the fundamental laws of nature, but it does not tell the whole story. Only experimental data using the higher energies reached by the LHC can push knowledge forward, challenging those who seek confirmation of established knowledge, and those who dare to dream beyond the paradigm.’

Extracts courtesy of CERN

The principles of physics used in the operation of the cathode ray tube (CRT) are also used in particle accelerators, including the LHC. The first switch-on of the LHC occurred on 10 September 2008.

## Why the LHC?

***A few unanswered questions...***

The LHC was built to help scientists to answer key unresolved questions in particle physics. The unprecedented energy it achieves may even reveal some unexpected results that no one has ever thought of!

For the past few decades, physicists have been able to describe with increasing detail the fundamental particles that make up the universe and the interactions between them. This understanding is encapsulated in the standard model of particle physics, but it contains gaps and cannot tell us the whole story. To fill in the missing knowledge requires experimental data, and the next big step to achieving this is with LHC.

### *Newton's unfinished business...*

**What is mass?**

What is the origin of mass? Why do tiny particles weigh the amount they do? Why do some particles have no mass at all? At present, there are no established answers to these questions. The most likely explanation may be found in the Higgs boson, a key undiscovered particle that is essential for the standard model to work. First hypothesised in 1964, it has yet to be observed.

The ATLAS and CMS experiments will be actively searching for signs of this elusive particle.

### *An invisible problem...*

**What is 96% of the universe made of?**

Everything we see in the universe, from an ant to a galaxy, is made up of ordinary particles. These are collectively referred to as matter, forming 4% of the universe. Dark matter and dark energy are believed to make up the remaining proportion, but they are incredibly difficult to detect and study, other than through the gravitational forces they exert. Investigating the nature of dark matter and dark energy is one of the biggest challenges today in the fields of particle physics and cosmology.

The ATLAS and CMS experiments will look for particles to test a likely hypothesis for the make-up of dark matter.

## *Nature's favouritism...*

### Why is there no more antimatter?

We live in a world of matter – everything in the universe, including ourselves, is made of matter. Antimatter is like a twin version of matter, but with opposite electric charge. At the birth of the universe, equal amounts of matter and antimatter should have been produced in the Big Bang. However, when matter and antimatter particles meet they annihilate each other, transforming into energy. Somehow, a tiny fraction of matter must have survived to form the universe we live in today, with hardly any antimatter left. Why does nature appear to have this bias for matter over antimatter?
The LHCb experiment will be looking for differences between matter and antimatter to help answer this question. Previous experiments have already observed a tiny behavioural difference, but what has been seen so far is not nearly enough to account for the apparent matter–antimatter imbalance in the universe.

## *Secrets of the Big Bang*

### What was matter like within the first second of the universe's life?

Matter, from which everything in the universe is made, is believed to have originated from a dense and hot cocktail of fundamental particles. Today, the ordinary matter of the universe is made of atoms, which contain a nucleus composed of protons and neutrons. These in turn are made of quarks bound together by other particles called gluons. The bond is very strong, but, in the very early universe, conditions would have been too hot and energetic for the gluons to hold the quarks together. Instead, it seems likely that during the first microseconds after the Big Bang the universe would have contained a very hot and dense mixture of quarks and gluons called quark–gluon plasma.

The ALICE experiment will use the LHC to recreate conditions similar to those just after the Big Bang, in particular to analyse the properties of the quark–gluon plasma.

## *Hidden worlds…*

### Do extra dimensions of space really exist?

Einstein showed that the three dimensions of space are related to time. Subsequent theories propose that further hidden dimensions of space may exist. For example, string theory implies that there are additional spatial dimensions yet to be observed. These may become detectable at very high energies, so data from all the detectors will be carefully analysed to look for signs of extra dimensions.

Extracts courtesy of CERN

## Facts and figures

**The largest machine in the world...**

The precise circumference of the LHC accelerator is 26,659 m, with a total of 9300 magnets inside. Not only is the LHC the world’s largest particle accelerator, just one-eighth of its cryogenic distribution system would qualify as the world’s largest fridge. All the magnets will be pre-cooled to –193.2°C (80 K) using 10 080 tonnes of liquid nitrogen, before they are filled with nearly 60 tonnes of liquid helium to bring them down to –271.3°C (1.9 K).

***The fastest racetrack on the planet...***

At full power, trillions of protons will race around the LHC accelerator ring 11,245 times a second, travelling at 99.99% the speed of light. Two beams of protons will each travel at a maximum energy of 7 TeV (tera-electronvolt), corresponding to head-to-head collisions of 14 TeV. Altogether some 600 million collisions will take place every second.

***The emptiest space in the Solar System...***

To avoid colliding with gas molecules inside the accelerator, the beams of particles travel in an ultra-high vacuum – a cavity as empty as interplanetary space. The internal pressure of the LHC is $10^{-13}$ atm, ten times less than the pressure on the Moon!

***The hottest spots in the galaxy, but even colder than outer space...***

The LHC is a machine of extreme hot and cold. When two beams of protons collide, they will generate temperatures more than 100,000 times hotter than the heart of the Sun, concentrated within a minuscule space. By contrast, the ‘cryogenic distribution system’, which circulates superfluid helium around the accelerator ring, keeps the LHC at a super cool temperature of –271.3°C (1.9 K) – even colder than outer space!

***The biggest and most sophisticated detectors ever built...***

To sample and record the results of up to 600 million proton collisions per second, physicists and engineers have built gargantuan devices that measure particles with micron precision. The LHC's detectors have sophisticated electronic trigger systems that precisely measure the passage time of a particle to accuracies in the region of a few billionths of a second. The trigger system also registers the location of the particles to millionths of a metre. This incredibly quick and precise response is essential for ensuring that the particle recorded in successive layers of a detector is one and the same.

***The most powerful supercomputer system in the world...***

The data recorded by each of the big experiments at the LHC will fill around 100,000 dual layer DVDs every year. To allow the thousands of scientists scattered around the globe to collaborate on the analysis over the next 15 years (the estimated lifetime of the LHC), tens of thousands of computers located around the world are being harnessed in a distributed computing network called the Grid.

Extracts courtesy of CERN

Key milestones in the construction of the LHC can be found on the CERN website at http://lhc-milestones.web.cern.ch/LHC-Milestones/

## How an accelerator works

Accelerators were invented to provide energetic particles to investigate the structure of the atomic nucleus. Since then, they have been used to investigate many aspects of particle physics. Their job is to speed up and increase the energy of a beam of particles by generating electric fields that accelerate the particles, and magnetic fields that steer and focus them.



An accelerator comes either in the form of a ring (circular accelerator), where a beam of particles travels repeatedly round a loop, or in a straight line (linear accelerator), where the beam travels from one end to the other. A number of accelerators may be joined together in sequence to reach successively higher energies, as at the accelerator complex at CERN.

The main components of an accelerator include:

- Radiofrequency (RF) cavities and electric fields – these provide acceleration to a beam of particles. RF cavities are located intermittently along the beam pipe. Each time a beam passes the electric field in an RF cavity, some of the energy from the radio wave is transferred to the particles.
- Vacuum chamber – this is a metal pipe (also known as the beam pipe) inside which a beam of particles travels. It is kept at an ultrahigh vacuum to minimise the amount of gas present to avoid collisions between gas molecules and the particles in the beam.
- Magnets – various types of magnets are used to serve different functions. For example, dipole magnets are usually used to bend the path of a beam of particles that would otherwise travel in a straight line. The more energy a particle has, the greater the magnetic field needed to bend its path. Quadrupole magnets are used to focus a beam, gathering all the particles closer together (similar to the way that lenses are used to focus a beam of light).

Collisions at accelerators can occur either against a fixed target, or between two beams of particles. Particle detectors are placed around the collision point to record and reveal the particles that emerge from the collision.

Extracts courtesy of CERN

### The physics of particle accelerators

There are three types of particle accelerators:

- cyclotron
- synchrotron
- linear accelerator (linacs).

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

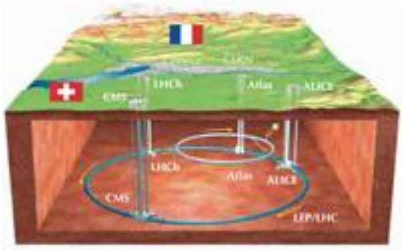
- a source of particles (this may be another accelerator)
- beam pipes (a guide along which the particles will travel whilst being accelerated)
- accelerating structures (a method of accelerating the particles)
- a system of magnets (either electromagnets or superconducting magnets as in the LHC)
- a target (in the LHC the target is a packet of particles travelling in the opposite direction).



http://www.scienceinschool.org/2008/issue10/lhchow

Published in *Science in School* (http://www.scienceinschool.org)

# The LHC: a look inside



**The LHC experiments.**
**Click to enlarge image**
Image courtesy of CERN

*In the second of two articles,* ***Rolf Landua*** *from CERN takes us deep below the ground to visit the largest scientific endeavour on Earth – the Large Hadron Collider and its experiments.*

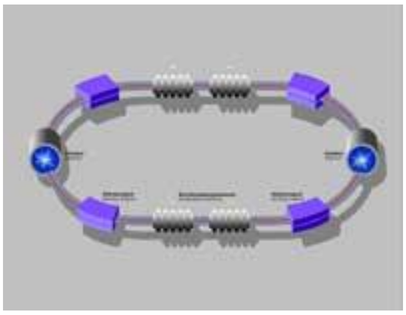
## The accelerator

The Large Hadron Collider[w1] (LHC) at the European Organization for Nuclear Research (CERN) is a gigantic scientific instrument spanning the Swiss-French border near Geneva, Switzerland. The world's largest and most powerful particle accelerator, it is used by almost 10 000 physicists from more than 80 countries to search for particles to unravel the chain of events that shaped our Universe a fraction of a second after the Big Bang. It could resolve puzzles ranging from the properties of the smallest particles to the biggest structures in the vastness of the Universe.

The design and construction of the LHC took about 20 years at a total cost of €3.6 billion. It is housed in a 27 km long and 3.8 m wide tunnel about 100 m underground. At this level, there is a geologically stable stratum, and the depth prevents any radiation from escaping. Until 2000, the tunnel was the home of the Large Electron-Positron (LEP) storage ring, which was built in 1989. This earlier accelerator collided electrons with their anti-particles, positrons (for an explanation of antimatter, see Landua & Rau, 2008), to study the properties of the resulting particles and their interactions with great precision. There are eight elevators leading down into the tunnel, and although the ride is only one stop, it takes a whole minute. To move between the eight access points, maintenance and security people use bicycles to move around the tunnel – sometimes for several kilometres. The LHC is automatically operated from a central control centre, so once the experiments have started, engineers and technicians will only have to access the tunnel for maintenance.

**While the LHC was being built, technicians used various means of transport to move around the 27 km tunnel. Alongside the technician, two LHC magnets can be seen, before they were connected together. The blue cylinders contain the magnetic yoke and coil of the dipole magnets, together with the liquid helium system required to cool the magnet so that it becomes superconducting**
Image courtesy of CERN

The actual experiment is a rather simple process: the LHC will collide two hadrons – either protons or lead nuclei – at close to the speed of light. The very high levels of energy involved will allow the kinetic energy of the colliding particles to be transformed into matter, according to Einstein's law $E = mc^2$, and all matter particles created in the collision will be detected and measured. This experiment will be repeated up to 600 million times per second, for many years. The LHC will mainly perform proton–proton collisions, which will be studied by three of its four detectors (ATLAS, CMS, and LHCb). However, for several weeks per year, heavy ions (lead nuclei) will be accelerated and collided instead, to be studied mainly by the dedicated ALICE detector.



**The principle of a particle accelerator with its three main components: the beam pipes, the acceleration elements, and the bending magnets. Click to enlarge image**
Image courtesy of DESY

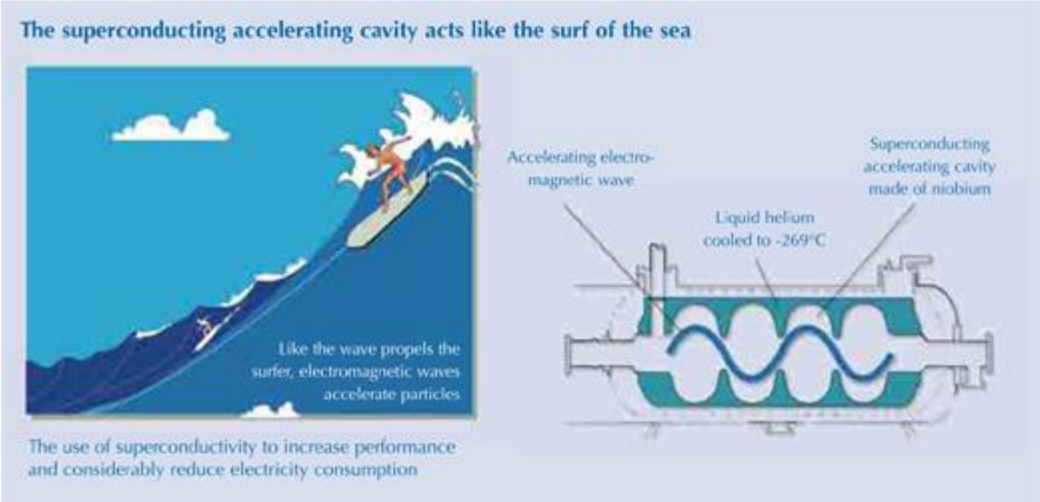
Like any other particle accelerator, the LHC has three main components: the beam pipes, the accelerating structures, and the magnet system (see diagram). Inside its two beam pipes, each 6.3 cm in diameter, proton (or heavy ion) beams travel in opposite directions (one direction in each pipe) in an ultra-high vacuum of $10^{-13}$ bar, comparable to the density of matter in outer space. This low pressure is necessary to minimise the number of collisions with resting gas molecules and the subsequent loss of the accelerated particles.

The protons are supplied from a hydrogen gas bottle. Hydrogen atoms consist of a proton and an electron. Scientists remove the electrons using an electric discharge, after which the protons are guided towards the accelerator through electric and magnetic fields. For the LHC beam, 300 trillion protons are required, but since a single cubic centimetre of hydrogen gas at room temperature contains about 60 million trillion protons, the LHC can be refilled 200 000 times with just one cubic centimetre of gas – and it only needs refilling twice a day!

The second part of an accelerator consists of its accelerating structures. Before protons (or heavy ions) are introduced into the two LHC beam pipes, they are accelerated in smaller accelerators (connected to the LHC) to about 6% of their final energy. Inside the LHC, the particles acquire their final energy from eight accelerating structures (accelerator cavities).

Every time the particles run through these cavities, they are accelerated by a strong electric field of about 5 MV/m. The functionality of the accelerators is comparable to surf on the sea (see diagram opposite): a bunch of protons, about 100 billion of them – the surfers – ride together on an enormous electromagnetic wave and gain kinetic energy. Each wave accelerates one bunch of protons, and each of the two beams consists of 2800 discrete bunches, one every seven metres. After 20 minutes, they reach their final energy, while doing 11 245 circuits of the LHC ring per second. In those 20 minutes, the protons cover a distance further than from Earth to the Sun and back.

**Cross-section of LHC prototype beam pipes showing the beam screens. Slits in the screens allow residual gas molecules to be pumped out and frozen to the walls of the ultra-cold beam pipe. Beam screens like these have been designed to line the beam pipes, absorbing radiation before it can hit the magnets and warm them up, an effect that would greatly reduce the magnetic field and cause serious damage**
Image courtesy of CERN



**The superconducting accelerating cavity acts like the surf of the sea**
Image courtesy of CERN

They enter the LHC at 99.9997828% of the speed of light. After acceleration, they reach 99.9999991%. This is about the maximum speed that can be reached, since nothing can move faster than light, according to the theory of relativity. Although it might seem like an insignificant gain in speed, at close to the speed of light, even a small acceleration results in a large gain in mass, and this is the important part. A motionless proton has a mass of 0.938 GeV (938 million electron volts). The accelerators bring them to a final mass (or energy, which in this case is practically the same thing) of 7000 billion electron volts (7 tera-eV or 7 TeV). If you could – hypothetically – accelerate a person of 100 kg in the LHC, his or her mass would end up being 700 t.


**This computer-generated image of an LHC dipole magnet shows some of the parts vital for the operation of these components. The magnets must be cooled to 1.9 K so that the superconducting coils can produce the required 8 T magnetic field. Click to enlarge image**
Image courtesy of CERN

Without external forces, the protons would fly in a straight line. To give them a circular trajectory, the pipes are surrounded by a large magnet system that deflects the protons' path – these magnets are the third part of every particle accelerator. The larger the mass of a particle becomes, the stronger the magnets need to be to keep it on track. This is where the limitations of a particle accelerator lie, since at a certain magnetic energy, the material of the magnetic coils cannot resist the forces of its own magnetic field anymore. The magnets used in the LHC have been specially designed: the dominant part of the magnet system consists of 1232 dipole magnets, each with a length of about 16 m and a weight of 35 t, which create a maximum magnetic field of 8.33 tesla – 150 000 stronger than Earth's magnetic field.

The magnets have a special two-in-one design: they contain two magnet coils on the inside, each surrounding one of the two beam pipes. The current runs through the coils to create two magnetic fields, pointing downwards in one pipe and upwards in the other. This is how two particles (protons or lead nuclei) of the same charge can follow the same track in opposite directions – one in each beam pipe.

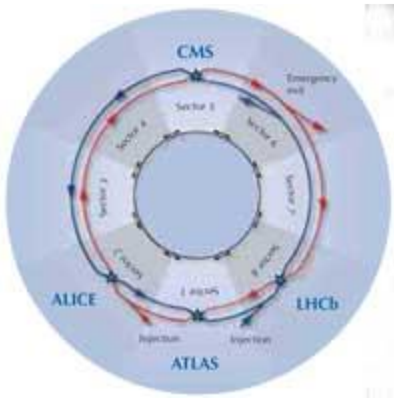
In addition to the dipole magnets, there are quadrupole magnets (with four magnetic poles) for focusing the beams, and thousands of additional smaller sextupole and octupole magnets (with six or eight magnetic poles each, respectively) for correcting the beam size and position.

All magnet coils and the accelerator cavities are built from special materials (niobium and titanium) that become superconducting at very low temperatures, conducting electricity to produce the electric and magnetic fields without resistance. To reach their maximum performance, the magnets need to be chilled to –271.3°C (1.9K) – a temperature colder than outer space. To cool the magnets, much of the accelerator is connected to a distribution system of liquid nitrogen and helium (see box). Just one-eighth of the LHC's cryogenic distribution system would qualify as the world's largest fridge.

Around the ring are four points at which the chain of magnets is broken: they contain the four huge caverns for the LHC experiments and their detectors.

Here, the trajectories of the inner and outer beams are made to cross each other and swap places in special X-shaped beam pipes. In all four X-shaped pipes, the beams cross at an angle of 1.5 degrees, allowing the beams to be brought into collision.

Huge detectors – described below – surround the collision points. To increase the probability of particle collisions, the bunches of particles are squeezed, by special magnets just in front of each collision chamber, to a diameter of 16 µm – thinner than a human hair – and 80 mm in length. The beams are so tiny that the task of making them collide is akin to firing needles from two positions 10 km apart with such precision that they meet halfway! However, the LHC technology manages this intricate task. Nonetheless, even in these focused beams of particles, the density is still very low – 100 million times lower than that of water – so most of the particles pass straight through the other bunch of particles without colliding or even slowing down. Thus, although there are 100 billion protons in each bunch, when two bunches collide, only about 20 particle collisions occur. Since collisions between two bunches occur 31 million times per second (2800 bunches × 11 245 turns of the LHC ring per second), this still gives about 600 million proton collisions per second when the LHC is operating at maximum intensity.



**The LHC experiments. Click to enlarge image**
Image courtesy of Nicola Graf

A single bunch of protons travelling at full speed has the same kinetic energy as a one-tonne elephant running at 50 km/h, and the entire energy contained in the beam is 315 megajoules (MJ), enough to melt nearly 500 kg of copper. Therefore, considerable efforts have gone into the security of the LHC. Should the beam become unstable, this will be immediately detected by the beam sensors, and within the next three laps around the ring (i.e. in less than a thousandth of a second) the beam will be deflected into a kind of emergency exit, where it is absorbed by graphite plates and concrete before it can cause any further damage (see diagram above).

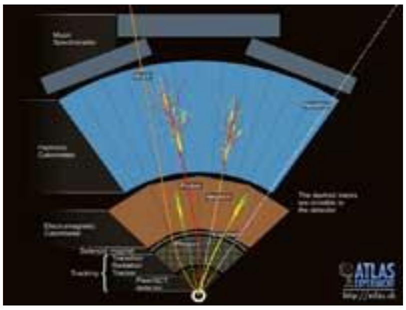
**The experiments**

The LHC will collide two protons at a total kinetic energy of 7 + 7 = 14 TeV (or two lead ions at a total energy of 1140 TeV), and then detect and measure the new particles produced when the kinetic energy is transformed into matter.

According to quantum physics, these collisions will generate all particles of the standard model (as described in Landua & Rau, 2008) with certain probabilities. However, the probability of generating the heavy particles that scientists are actually looking for is very low. Few of the particle collisions will be hard enough to produce new, heavy particles. Theory predicts that Higgs bosons (to learn more about the Higgs boson, see Landua & Rau, 2008) or other completely new phenomena that are being searched for will be produced only very rarely (typically once in $10^{12}$ collisions), so it is necessary to study many collisions in order to find the ‘needle in a million haystacks’. That is why the LHC will be run for many years, 24 hours a day.

The events (an event is a collision with all its resulting particles) are studied using giant detectors that are able to reconstruct what happened during the collisions – and to keep up with the enormous collision rates. Detectors can be compared to huge three-dimensional digital cameras that can take up to 40 million snapshots (with digitised information from tens of millions of sensors) per second. The detectors are built in layers, and each layer has a different functionality (see diagram below). The inner ones are the least dense, while the outer ones are denser and more compact.

The heavy particles that scientists hope to produce in the LHC collisions are predicted to be very short-lived, rapidly decaying into lighter, known particles. After a hard collision, hundreds of these lighter particles, for example electrons, muons and photons, but also protons, neutrons and others, fly through the detector at close to the speed of light. Detectors use these lighter particles to deduce the brief existence of the new, heavy ones.




**A computer-generated image of the ATLAS detector, showing the different layers and the passage of different particle types through the layers. Click to enlarge image**
Image courtesy of CERN

The trajectories of charged particle are bent by magnetic fields, and their radius of curvature is used to calculate their momentum: the higher the kinetic energy, the shallower the curvature. For particles with high kinetic energy, therefore, a sufficiently long trajectory must be measured in order to accurately determine the curvature radius. Other important parts of a detector are calorimeters for measuring the energy of particles (both charged and uncharged). The calorimeters too have to be large enough to absorb as much particle energy as possible. These are the two principle reasons why the LHC detectors are so large.

The detectors are built to enclose the interaction region in order to account for the total energy and momentum balance of each event and to reconstruct it in detail. Combining the information from the different layers of the detector, it is possible to determine the type of particle which has left each trace.

Charged particles – electrons, protons and muons – leave traces through ionisation. Electrons are very light and therefore lose their energy quickly, while protons penetrate further through the layers of the detector. Photons themselves leave no trace, but in the calorimeters, each photon converts into one electron and one positron, the energies of which are then measured. The energy of neutrons is measured indirectly: neutrons transfer their energy to protons, and these protons are then detected. Muons are the only particles that reach (and are detected by) the outermost layers of the detector (see diagram above).

Each part of a detector is connected to an electronic readout system via thousands of cables. As soon as an impulse is registered, the system records the exact place and time and sends the information to a computer. Several hundred computers work together to combine the information. At the top of the computer hierarchy is a very fast system which decides – in a split second – whether an event is interesting or not. There are many different criteria to select potentially significant events, which is how the enormous data of 600 million events is reduced to a few hundred events per second that are investigated in detail.

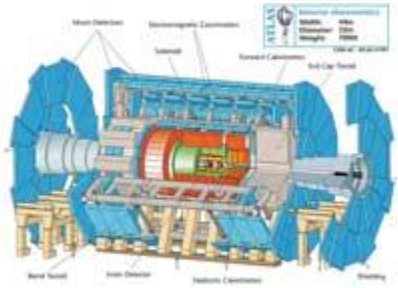
The LHC detectors were designed, constructed and commissioned by international collaborations, bringing together scientists from institutes all over the world. In total, there are four large (ATLAS, CMS, LHCb and ALICE) and two small (TOTEM, LHCf) experiments at the LHC. Considering that it took 20 years to plan and construct the detectors, and they are intended to run for more than 10 years, the total duration of the experiments is almost equivalent to the entire career of a physicist.

The construction of these detectors is the result of what could be called'group intelligence': while the scientists working on a detector understand the function of the apparatus in general, no one scientist is familiar with the details and precise function of each single part. In such collaboration, every scientist contributes with his or her expertise to the overall success.

**ATLAS and CMS**

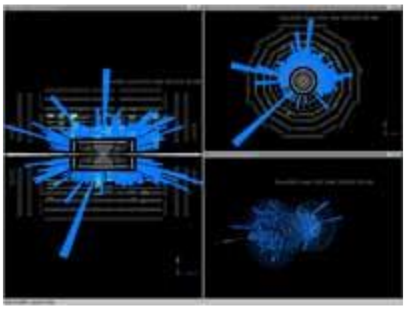
The two largest experiments, ATLAS[w2] (A Toroidal LHC Apparatus) and CMS[w3] (Compact Muon Solenoid), are general-purpose detectors optimised for the search for new particles. ATLAS and CMS are located on opposite sides of the LHC ring, 9 km apart (see diagram of the experiments). Having two independently designed detectors is vital for cross-confirmation of any new discoveries.

The ATLAS and the CMS collaborations each consist of more than 2000 physicists from 35 countries. The ATLAS detector has the shape of a cylinder 25 m in diameter and 45 m in length, about half as big as Notre Dame Cathedral in Paris, France, and weighing the same as the Eiffel Tower (7000 t). Its magnetic field is produced by a solenoid in the inner part and an enormous doughnut-shaped toroid magnet further outside (see diagram, right).



**The ATLAS detector will be the largest of its type in the world when its construction is completed; the people in the diagram are to scale. Click to enlarge image**

Image courtesy of CERN



**One of the first images from CMS, showing the debris of particles recorded by the detector's calorimeters and muon chambers. Click to enlarge image**
Image courtesy of CERN

The CMS detector also has a cylindrical shape (15m in diameter and 21m in length) and is built around a superconducting solenoid magnet generating a field of 4 tesla, which is confined by a steel yoke that forms the bulk of the detector's weight of 12 500 t. While ATLAS was constructed in situ, the CMS detector was constructed at the surface, lowered underground in 15 sections and then assembled.

**LHCb**

The LHCb[w4] experiment will help us to understand why we live in a universe that appears to be composed almost entirely of matter but no antimatter. It specialises in investigating the slight differences between matter and antimatter by studying a type of particle called the bottom quark, or b quark (see Landua & Rau, 2008, for an explanation of antimatter and quark types). To identify and measure the b quarks and their antimatter counterparts, the anti-b quarks, LHCb has sophisticated movable tracking detectors close to the path of the beams circling in the LHC.

**The leading members of the LHCb magnet project; also visible are the coils of the detector's huge dipole magnet. April 2004**
Image courtesy of CERN

**ALICE**

ALICE[w5] (A Large Ion Collider Experiment) is a specialised detector for analysing the collisions of lead ions. For a few weeks each year these, rather than protons, will be collided in the LHC. Within the dimensions of an atomic nucleus, this will create conditions that prevailed about a millionth of a second after the Big Bang, when the temperature of the entire Universe was about 100 000 times hotter than the interior of the Sun. These conditions might create a state of matter called a quark-gluon plasma, the characteristics of which physicists hope to study (for a further explanation of the quark-gluon plasma, see Landua, 2008).

**Integration of the ALICE experiment's inner tracker**
Image courtesy of CERN

**The data challenge**

The LHC will produce roughly 15 petabytes (15 million gigabytes) of data annually – enough to fill more than 3 million DVDs. Thousands of scientists around the world want to access and analyse these data, so CERN is collaborating with institutions in 33 countries to operate a distributed computing and data storage infrastructure: the LHC Computing Grid (LCG).

The LCG will allow data from the LHC experiments to be distributed around the globe, with a primary backup kept at CERN. After initial processing, the data will be distributed to eleven large computer centres. These tier-1 centres will make the data available to more than 120 tier-2 centres for specific analysis tasks. Individual scientists can then access the LHC data from their home country, using local computer clusters or even individual PCs.

*Who works on the LHC?*

***Liz Gregson** from Imperial College London, UK, talks to some of the CERN employees.*

***Katharine Leney, ATLAS physicist***

**Katharine Leney**
Image courtesy of Mike Flowerdew

Katharine is doing a PhD in physics on the search for the Higgs boson, working on the ATLAS detector. She is also developing a tool to look at conditions within the detector, to ensure that the data obtained will be usable. 'It's a really exciting time to be here, working alongside some of the world's top physicists.' In addition to her research, she has recently become a CERN guide, showing visitors the experiments and explaining the work that scientists do there.

***Dr Marco Cattaneo, project co-ordination***

Marco was born in Italy and moved to the UK at the age of ten. Today he lives in France, works in Switzerland, and has a Swiss–British wife and two children who can speak three languages fluently. 'When asked what I am, I can only answer European!' he says. He has been at CERN since 1994. He is deputy project leader on the software and computing project for the LHCb experiment. His main job is to co-ordinate the work of around 50 physicists who develop software that enables reconstructions of the original trajectories of the particle collisions recorded by the detector. This is then integrated into a single reconstruction programme, so that others can study the characteristics of the collision event.

**Dr Marco Cattaneo**
Image courtesy of CERN

Marco enjoys the work atmosphere at CERN: 'It attracts about 50 percent of the world's particle physics community, meaning that the vast majority of people working at CERN are highly skilled in their field and very motivated by their work. It is not unusual to be on first-name terms with Nobel laureates.'

*This text was first published in the Imperial College London alumni magazine, Imperial Matters.*

In the first article of this pair (Landua & Rau, 2008), Rolf Landua and Marlene Rau introduce the particle physics behind the LHC.

**References**

Landua R, Rau M (2008) The LHC: a step closer to the Big Bang. *Science in School* **10**: 26-33.www.scienceinschool.org/2008/issue10/lhcwhy

**Web references**

w1 – A guide to the Large Hadron Collider can be found here: http://cdsweb.cern.ch/record/1092437/files/CERN-Brochure-2008-001-Eng.pdf
A video of the Large Hadron Rap can be viewed here: www.youtube.com/watch?v=j50ZssEojtM
w2 – For more information on the ATLAS experiment, see: http://atlas.ch
w3 – For more information on the CMS experiment, see: http://cms-project-cmsinfo.web.cern.ch/cms-project-cmsinfo/index.html
w4 – For more information on the LHCb experiment, see: http://lhcb-public.web.cern.ch/lhcb-public
w5 – For more information on the ALICE experiment, see: http://aliceinfo.cern.ch/Public/Welcome.html

**Resources**

A much more detailed account of the standard model and the LHC experiments can be found in Rolf Landua's German-language book:
Landua R (2008) *Am Rand der Dimensionen*. Frankfurt, Germany: Suhrkamp Verlag
Boffin H (2008) 'Intelligence is of secondary importance in research'. *Science in School* **10**: 14-19. www.scienceinschool.org/2008/issue10/tamaradavis
Warmbein B (2007) Making dark matter a little brighter. *Science in School* **5**: 78-80. www.scienceinschool.org/2007/issue5/jennylist
The CERN website devotes a substantial amount of space to the LHC; see: http://public.web.cern.ch/public/en/LHC
The CERN pages offer a wealth of teaching material on particle physics and accelerators: http://education.web.cern.ch/education/Chapter2/Intro.html
Among the teaching material on the CERN website is an online LHC game in English, French, German and Italian:
http://microcosm.web.cern.ch/microcosm/LHCGame/LHCGame.html

The LHC UK website includes materials about the LHC for teachers and students: www.lhc.ac.uk

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*Rolf Landua is the Head of Education at CERN, where he has been working since 1980. A German particle physicist, he is the co-initiator of the Antimatter Factory at CERN and led the ATHENA project that created millions of anti-hydrogen atoms in 2002. He is secretly famous as the model for the character of Leonardo Vetra, an antimatter physicist from CERN who is murdered in the first pages of Dan Brown's bestseller Angels and Demons, which is being turned into a Hollywood film due for release in May 2009. He runs courses at CERN for physics teachers from across Europe, is a regular interview partner on radio and TV and has recently released a German-language book on CERN particle physics (Am Rand der Dimensionen, On the Border of the Dimensions, see resources). For his commitment to fostering science education in schools, he received the 2003 European Physical Society's communication award.*

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**Source URL:** http://www.scienceinschool.org/2008/issue10/lhchow
If you have read the Dan Brown book *Angels and Demons* or seen the film of the same name, then you will have heard of CERN and the LHC in the context of a secret society that wants to destroy the Vatican using an antimatter bomb with antimatter created in the LHC. Rest assured, it is a work of fiction, but with its roots in the amazing research happening at particle accelerator sites around the world. More information can be found on the CERN website: http://angelsanddemons.cern.ch/.

## Nuclear reactions: fission and fusion

Nuclear power has been used to produce electricity in the UK since 1956, when the first large-scale power plant was opened in Cumbria, England. It currently accounts for 10–15% of the UK's energy needs, although in the past it made a more significant contribution.

The first reactor to produce electricity was in Idaho, USA, opening in 1951. It produced sufficient electricity to illuminate four light bulbs. Its purpose was not to produce electricity on a commercial scale but to operate as an experimental reactor.

In 1954, Russia generated the first electricity for commercial use using nuclear power. Just under two years later, the UK's first plant, Calder Hall, produced ten times the power of the Russian plant. In late 2010, there were 441 nuclear plants in 30 countries worldwide

(source: http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-world-wide.htm,).

Nuclear power remains a controversial issue. It produces vast amounts of electricity without the production of carbon dioxide, which is associated with climate change. It is a very reliable source of energy. However, the waste it produces is radioactive and must be stored, sealed, for thousands of years, during which time it must be protected, eg from geological threats such as earthquakes and volcanic eruptions.

## Einstein and nuclear energy

Scientists' work on the standard model and subatomic particles, as well as addressing fundamental questions about the structure of matter, has led to the harnessing of the power of the nucleus – nuclear energy.

In 1905, a series of four papers by Albert Einstein was published in the journal *Annalen der Physik*. One of these 'Does the inertia of a body depend upon its energy content' led us to one of the best-known relationships in the world:

$$E = mc^2$$

**But what does this mean? And what is its significance?** In terms of quantities and units, there is nothing particularly challenging in this relationship.

| | |
|---|---|
| $E = mc^2$ | $E$ is energy measured in joules (J)<br>$m$ is mass measured in kilograms (kg)<br>$c$ is the speed of light in a vacuum (m $s^{-1}$) |

Its importance must be in its significance. The best person to explain this is Albert Einstein himself. You can listen to his explanation here:

http://www.aip.org/history/einstein/voice1.htm.

This website shows a useful timeline of scientific discovery relevant to the equation $E = mc^2$.

http://www.pbs.org/wgbh/nova/teachers/activities/3213_einstein_06.html

This website offers more detail to better understand the equation $E = mc^2$.

http://www.pbs.org/wgbh/nova/teachers/activities/3213_einstein_04.html

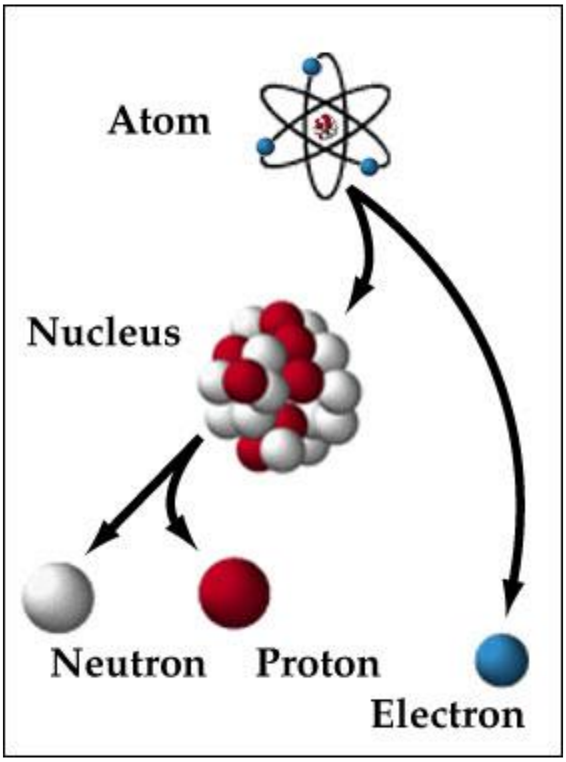
## A basic model of the atom

When we consider nuclear energy, we are dealing with energy released from the nucleus of the atom. A basic model of the atom, and its nucleus, is required.

In this model the nucleus consists of **protons**, with mass number 1 and charge +1, and **neutrons,** with mass number 1 and charge 0. Protons and neutrons are collectively known as **nucleons**.

- The total number of protons and neutrons in the nucleus is called the **mass number, A**.
- The number of protons in the nucleus is called the **atomic number, Z**.
- In a neutral atom the number of protons equals the number of electrons.

Components of the atom




http://www.atomicarchive.com/Physics/Physics1.shtml

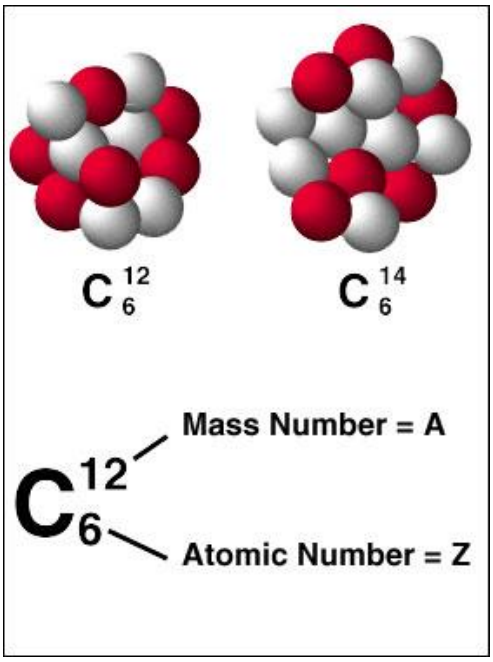
The mass numbers, charges and symbols for protons, neutrons and electrons are given below.

| Particle | Mass number | Charge | Symbol |
|---|---|---|---|
| Proton | 1 | +1 | $^1_1p$ |
| Neutron | 1 | 0 | $^1_1n$ |
| Electron | 0* | -1 | $^{1}_{-1}e$ |

*The mass of an electron is = 1/1840 of the mass of a proton.

Each **element** in the periodic table has a different atomic number and is identified by that number. It is possible to have different versions of the same element, called **isotopes**. An isotope of an atom has the same number of protons but a **different** number of neutrons, i.e. the same atomic number but a different mass number.

An isotope is identified by specifying its chemical symbol along with its atomic and mass numbers. For example:




Nuclear isotopes

http://www.atomicarchive.com/Physics/Physics1.shtml

**Radioactive decay**

Radioactive **decay** is the breakdown of a nucleus to release energy and matter from the nucleus. This is the basis of the word ‘nuclear’. The release of energy and/or matter allows unstable nuclei to achieve stability. Unstable nuclei are called **radioisotopes** or **radionuclides**.

The following is a summary of the nature and symbols for the three types of nuclear radiation. Notice that gamma radiation has zero mass and zero charge. It is an electromagnetic wave.

| Radiation | Nature | Symbol |
|---|---|---|
| Alpha particle | Helium nucleus | ${}^{4}_{2}He$ $\alpha$ |
| Beta particle | Fast electron | ${}^{0}_{-1}e$ $\beta$ |
| Gamma ray | High frequency electromagnetic wave | $\gamma$ |

Note that the beta particle is an electron released from the nucleus. It is not an orbiting electron. In the previous section, the basic model of the atom indicated that the nucleus comprises protons and neutrons. So where does this electron come from?

**Radioactive decay: representing by symbols and equations**

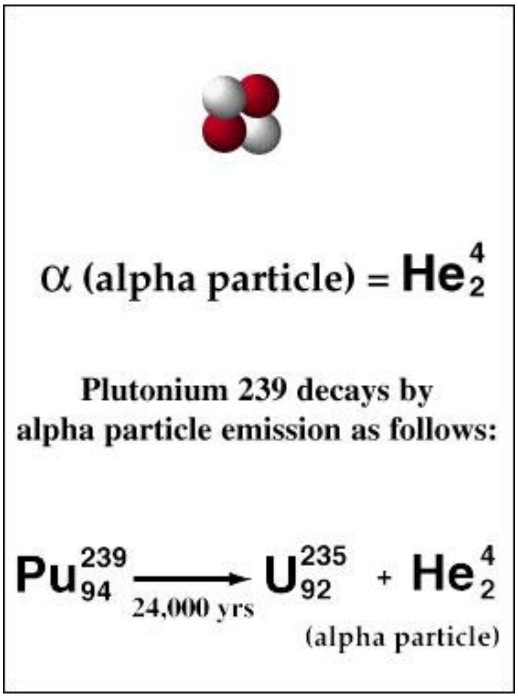
In the following equations both mass number and atomic number are **conserved**, ie the totals are the same before and after the decay.

The original radionuclide is called the **parent** and the new radionuclide produced after decay is called the **daughter product** (Which sometimes may go on to decay further).

**Alpha decay**

http://www.atomicarchive.com/Physics/Physics1.shtml

In alpha decay, a positively charged particle, identical to the nucleus of helium 4, is emitted spontaneously. This particle, also known as an alpha particle, consists of two protons and two neutrons. It was discovered and named by Sir Ernest Rutherford in 1899.



Alpha decay

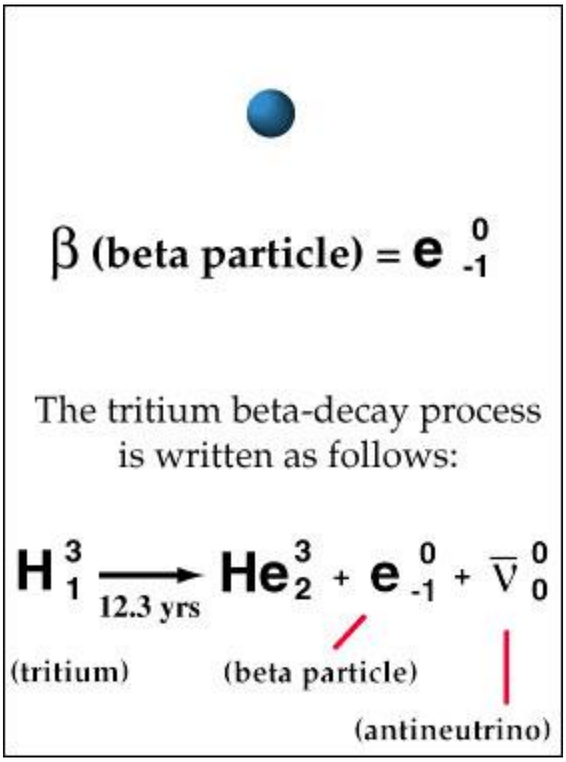
Alpha decay usually occurs in heavy nuclei such as uranium or plutonium, and therefore is a major part of the radioactive fallout from a nuclear explosion. Since an alpha particle is relatively more massive than other forms of radioactive decay, it can be stopped by a sheet of paper and cannot penetrate human skin. A 4 MeV alpha particle can only travel a few centimetres through the air.

Although the range of an alpha particle is short, if an alpha decaying element is ingested, the alpha particle can do considerable damage to the surrounding tissue. This is why plutonium, with a long half-life, is extremely hazardous if ingested.

**Beta decay**

http://www.atomicarchive.com/Physics/Physics7.shtml

Atoms emit beta particles through a process known as beta decay. Beta decay occurs when an atom has either too many protons or too many neutrons in its nucleus. Two types of beta decay can occur. One type (positive beta decay) releases a positively charged beta particle, called a positron, and a neutrino; the other type (negative beta decay) releases a negatively charged beta particle, called an electron, and an antineutrino. The neutrino and the antineutrino are high-energy elementary particles with little or no mass and are released in order to conserve energy during the decay process. Negative beta decay is far more common than positive beta decay.




Beta decay

This form of radioactive decay was discovered by Sir Ernest Rutherford in 1899,although the neutrino was not observed until the 1960s. Beta particles have all the characteristics of electrons. At the time of their emission, they travel at nearly the speed of light. A typical 0.5 MeV particle will travel about 3 m through the air, and can be stopped by 4-6 cm of wood.

**Gamma decay**

http://www.atomicarchive.com/Physics/Physics8.shtml

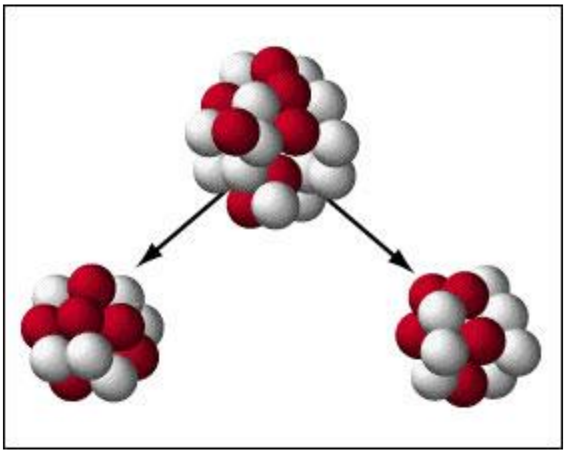
Gamma rays are a type of electromagnetic radiation that results from a redistribution of electric charge within a nucleus. Gamma rays are essentially very energetic X - rays; the distinction between the two is not based on their intrinsic nature but rather on their origins. X rays are emitted during atomic processes involving energetic electrons. Gamma radiation is emitted by excited nuclei or other processes involving subatomic particles; it often accompanies alpha or beta radiation, as a nucleus emitting those particles may be left in an excited (higher-energy) state.

Gamma rays are more penetrating than either alpha or beta radiation, but less ionising. Gamma rays from nuclear fallout would probably cause the largest number of casualties in the event of the use of nuclear weapons in a nuclear war. They produce damage similar to that caused by X-rays, such as burns, cancer and genetic mutations.

**Fission: spontaneous decay and nuclear bombardment**

http://www.atomicarchive.com/Physics/Physics9.shtml

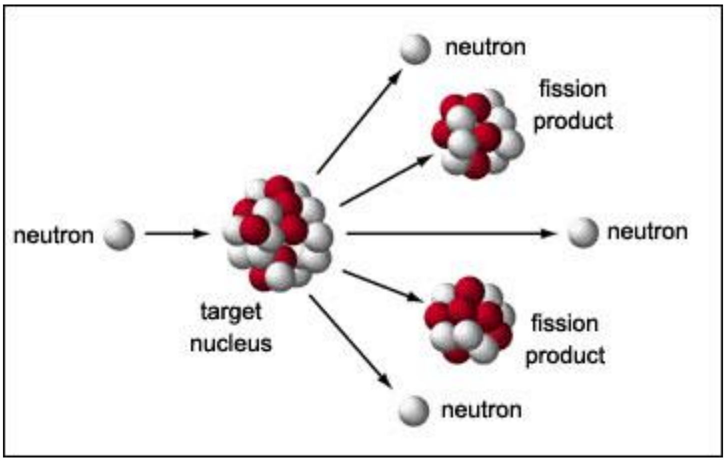
Fission occurs when a heavy nucleus disintegrates, forming two nuclei of smaller mass number. This radioactive decay is spontaneous fission. In this decay process, the nucleus will split into two nearly equal fragments and several free neutrons. A large amount of energy is also released. Most elements do not decay in this manner unless their mass number is greater than 230.



Spontaneous fission

The stray neutrons released by a spontaneous fission can prematurely initiate a chain reaction. This means that the assembly time to reach a critical mass has to be less than the rate of spontaneous fission. Scientists have to consider the spontaneous fission rate of each material when designing nuclear weapons or for nuclear power.
For example, the spontaneous fission rate of plutonium 239 is about 300 times larger than that of uranium 235.

Fission can also be induced, ie persuaded, to happen by **neutron bombardment**:




Nuclear fission

http://www.atomicarchive.com/Fission/Fission1.shtml

and in the equation:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

Consider: why is a neutron used for the bombardment process rather than, for example, a proton.

**Nuclear fission and $E = mc^2$**

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

Mass number and atomic number are both conserved during this fission reaction. Even though the mass number is conserved, when the masses before and after the fission are compared accurately, there is a **mass difference** (or **mass defect**). The total mass before fission is greater than the total mass of the products. This brings us back to Einstein's work, proposing a relationship between mass and energy:

| | |
|---|---|
| $E = mc^2$ | $E$ is energy measured in joules (J)<br>$m$ is mass difference measured in kilograms (kg)<br>ie total mass after fission – total mass before fission<br>$c$ is the speed of light in a vacuum (m $s^{-1}$) |

In fission reactions, the energy released is carried away as the **kinetic energy** of the fission products.

## Einstein and nuclear energy III

Einstein was not involved in the development of the world's first atomic weapons. However, so concerned was he about the potential for Germany to develop such weapons in advance of the Allies, on 2 August 1969 he wrote to the President of the United States of America, Franklin D Roosevelt, warning him of the possibility (http://www.aip.org/history/einstein/ae43a.htm). Einstein later indicated that urging the USA to develop nuclear weapons was the 'greatest mistake of his life' (http://www.aip.org/history/einstein/ae44.htm). Whether or not Germany was developing, or had developed, the capability for atomic weapons remains controversial and the evidence unclear. Further information on the Manhattan Project, the project to develop usable nuclear weapons during World War II, can be found at http://www.atomicheritage.org/index.php?option=com_content&task=view&id=45&Itemid=61. Six thousand scientists, under the leadership of Robert Oppenheimer, worked in complete secrecy on the project. Below are Robert Oppenheimer's words on the day of the first successful test, named Trinity, on Monday 16 July 1946 at 05:30.

> We knew the world would not be the same. A few people laughed, a few people cried, most people were silent. I remembered the line from the Hindu scripture, the Bhagavad-Gita. Vishnu is trying to persuade the Prince that he should do his duty and to impress him takes on his multi-armed form and says, 'Now, I am become Death, the destroyer of worlds.' I suppose we all thought that one way or another.
>
> J. Robert Oppenheimer

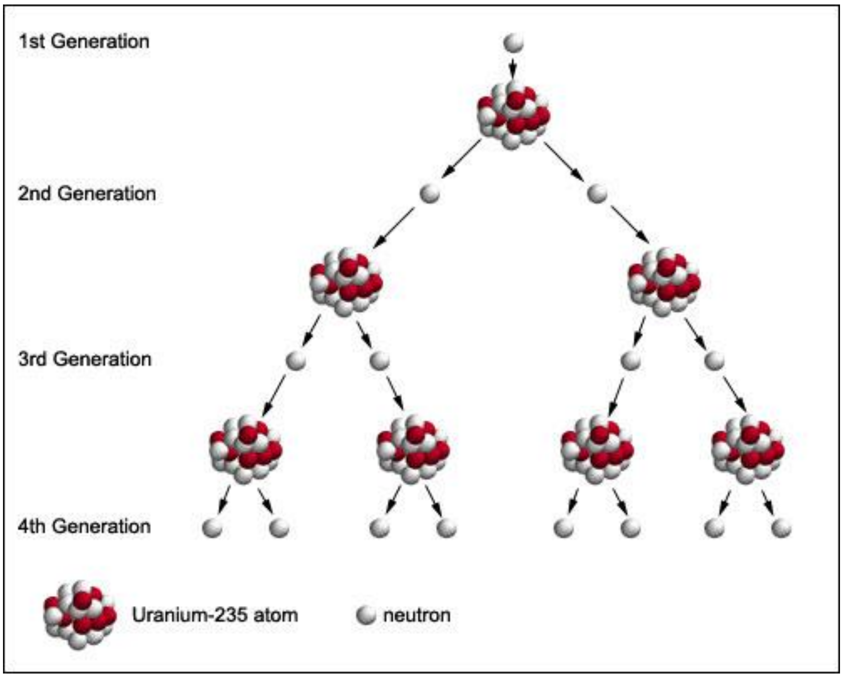
You can hear and watch Oppenheimer at http://www.atomicarchive.com/Movies/Movie8.shtml.

The mushroom cloud from the Trinity test.
http://www.atomicarchive.com/History/mp/p5s6.shtml

## Chain reactions

http://www.atomicarchive.com/Fission/Fission2.shtml

A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus. This nucleus in turn produces neutrons, and the process repeats. The process may be controlled (nuclear power) or uncontrolled (nuclear weapons).




$U^{235}$ + n ⟶ fission + 2 or 3 n + 200 MeV

If each neutron releases two more neutrons, then the number of fissions doubles each generation. In that case, in 10 generations there are 1024 fissions and in 80 generations about $6 \times 10^{23}$ (a mole) of fissions.

### Energy released from each fission

| | |
|---|---|
| 165 MeV | ~ kinetic energy of fission products |
| 7 MeV | ~ gamma rays |
| 6 MeV | ~ kinetic energy of the neutrons |
| 7 MeV | ~ energy from fission products |
| 6 MeV | ~ gamma rays from fission products |
| 9 MeV | ~ anti-neutrinos from fission products |
| **200 MeV** | |

1 MeV (million electron volts) = $1.609 \times 10^{13}$ joules

**Example**

Calculate the energy released during this fission reaction.

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{137}_{56}\text{Ba} + ^{97}_{42}\text{Mo} + 2\,^{1}_{0}\text{n} + \text{energy}$$

| Mass before fission (kg) | | Mass after fission (kg) | |
|---|---|---|---|
| U | $390.2 \times 10^{-27}$ | Ba | $227.3 \times 10^{-27}$ |
| n | $1.675 \times 10^{-27}$ | Mo | $160.9 \times 10^{-27}$ |
| | | 2n | $3.350 \times 10^{-27}$ |
| | $391.875 \times 10^{-27}$ | | $391.550 \times 10^{-27}$ |

Decrease in mass = $(391.875 – 391.550) \times 10^{-27} = 0.325 \times 10^{-27}$ kg

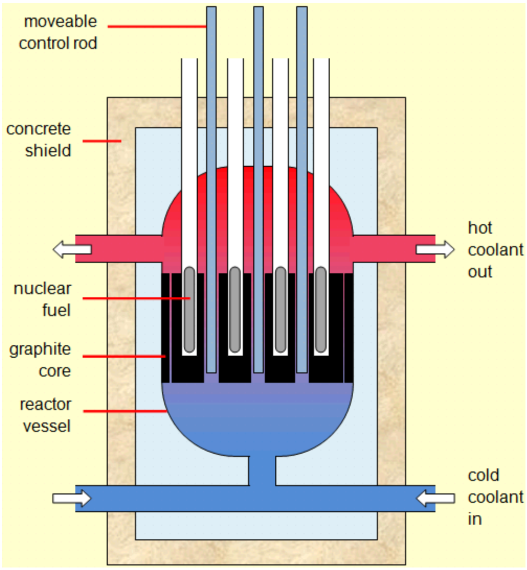
Energy released during this fission reaction, using $E = mc^2$

$$E = 3.25 \times 10^{-28} \times (3 \times 10^{8})^2 = 2.9 \times 10^{-11}\ \text{J}$$

This is the energy released by fission of a single nucleus.

Note the need to work with six significant figures for mass due to the small difference.

## Nuclear fission in nuclear reactors




Controlled fission reactions take place in nuclear reactors. The neutrons released are fast moving. A moderator, eg graphite, is used to slow them down and increase the chance of further fissions occurring. These slow (thermal) neutrons cause a chain reaction so that more fissions occur.

Control rods, eg boron, absorb some of the slow neutrons and keep the chain reaction under control. The energy of the moving fission products is transferred by heating in the reactor core. A coolant fluid (liquid or gas) is required to avoid the core overheating and in addition it can act as a moderator. The fluid turns into steam and this drives the turbines.

Fission reactors require containment within reinforced concrete and lead-lined containers to reduce contamination.

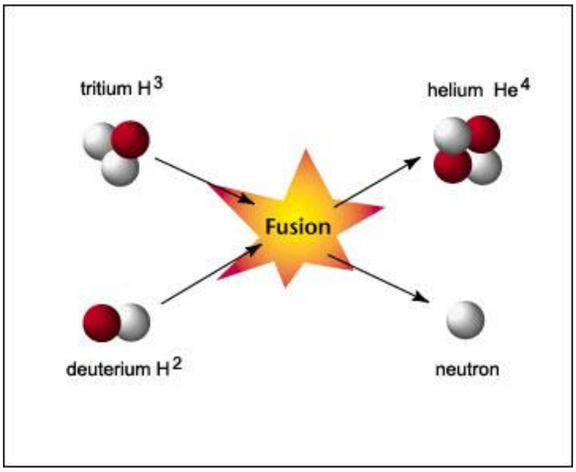
Using your prior knowledge of specific latent heat, you should be able to explain why turning the fluid into steam cools the reactor core.

www.edulink.networcs.net/sites/teachlearn/science/Image%20Library/Forms/DispForm.aspx?ID=49

## Nuclear fusion: energy of the future?

For some time, governments have sought to become less reliant on nuclear fission. However, as we face a future in which oil and other fossil fuel resources become increasingly scarce, it may become necessary for society to either re-examine approaches to reducing our demand on these resources or seek alternatives. Fuelling the world's ever-increasing population in the future may require another nuclear solution.

Watch the following short talk 'Fusion is energy's future' by physicist Steven Cowley, chief executive officer of the United Kingdom Atomic Energy Authority and head of the EURATOM/CCFE Fusion Association at http://www.ted.com/talks/lang/eng/steven_cowley_fusion_is_energy_s_future.html (just under 10 minutes). Also, read the article at http://www.guardian.co.uk/commentisfree/2010/jul/16/fusion-power-research-funding.




Nuclear fusion

Nuclear energy can also be released by the fusion of two light elements (elements with low atomic numbers).

In a hydrogen bomb, two isotopes of hydrogen, deuterium and tritium are fused to form a nucleus of helium and a neutron. This fusion releases 17.6 MeV of energy. Unlike nuclear fission, there is no limit on the amount of the fusion that can occur.

The immense energy produced by our Sun is as a result of nuclear fusion. Very high temperatures in the Sun ($2.3 \times 10^7$ K according to NASA; see http://imagine.gsfc.nasa.gov/docs/ask_astro/answers/981216a.html) supply sufficient energy for nuclei to overcome repulsive forces and fuse together.

When nuclei fuse, the final mass is less than the initial mass, ie there is a mass difference or mass defect. The energy produced can be calculated using:

| | |
|---|---|
| $E = mc^2$ | $E$ is energy measured in joules (J)<br>$m$ is the mass difference measured in kilograms (kg), ie total mass after fission – total mass before fission<br>$c$ is the speed of light in a vacuum (m $s^{-1}$) |

Deuterium is an isotope of hydrogen with two protons in its nucleus (heavy hydrogen). Tritium is another hydrogen isotope (super heavy hydrogen) with three protons in its nucleus. Deuterium is naturally occurring in seawater and tritium can be made from lithium, which is readily available on Earth.

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 (see http://www.jet.efda.org/).

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

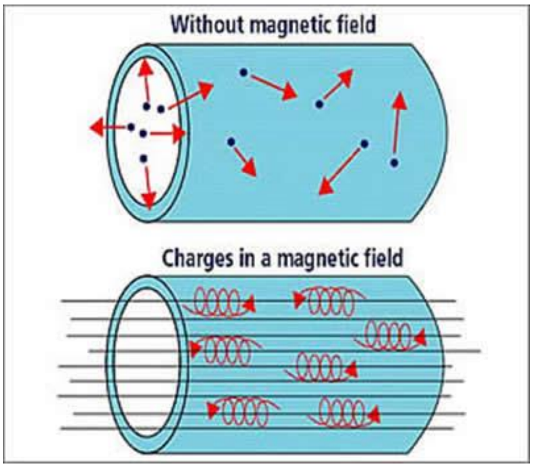
- plasma temperature ($T$): 100–200 million Kelvin
- energy confinement time ($t$): 4–6 seconds

- central density in plasma ($n$): 1–2 × $10^{20}$ particles $m^{-3}$ (approx. 1/1000 gram $m^{-3}$, ie one millionth of the density of air).

Note that at higher plasma densities the required confinement time will be shorter but it is very challenging to achieve higher plasma densities in realistic magnetic fields.



A short video of the contained plasma can be found at http://www.jet.efda.org/multimedia/video-gallery/pulse78125/.

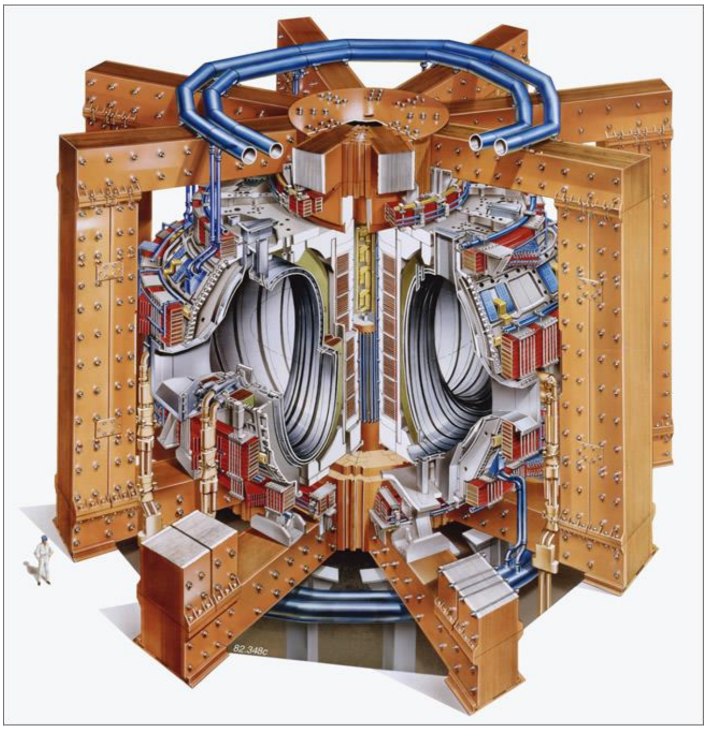



In a Tokamak the plasma is heated in a ring-shaped vessel (or torus) and kept away from the vessel walls by applied magnetic fields. The basic components of the Tokamak's magnetic confinement system are:

- The toroidal field – which produces a field around the torus. This is maintained by magnetic field coils surrounding the vacuum vessel (see figure). 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 (ie 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 out 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 (ie no external plasma heating is required). This condition is referred to as ignition. In magnetic plasma confinement of the D–T fusion reaction, the condition for ignition is approximately six times more demanding (in confinement time or in plasma density) than the condition for breakeven.'

## 2.4 Wave–particle duality

**History – The nature of light**

Exactly what is light? This question has troubled scientists since the time of the ancient Greeks, when Aristotle and Democritus started to publicly theorise. In ancient India, the Hindu schools of Samkhya and Vaisheshika were similarly divided between the two main theories: light is a wave or light is a stream of particles. Aristotle considered that light was a disturbance in the element, air, i.e. a wave. Democritus, who originally proposed the concept of atoms, not surprisingly thought that light is made up of 'corpuscules' or tiny particles of some form. At various points in history one view has held sway over the other as new experimental evidence came to light. For many of the properties of light it doesn't actually matter which view we take. Both theories can describe light as rays which travel in straight lines. Euclid was the first to develop a detailed theory of reflection using such rays. Nobody was able to develop theories of light much further as more intricate experimentation was not possible.

At the beginning of the 11th century the Arabic scientist Alhazen developed a full theory of optics (reflection, refraction and diffraction) based on a particle perspective. However, once again there was no significant progress for many centuries until Newton and his contemporaries locked horns in the 17th century. Newton considered that the particle nature of light was evident since only particles could travel in such perfectly straight lines. Refraction was more difficult to explain but he postulated that there would be a lateral acceleration on the particles as they changed medium. René Déscartes, Robert Hooke and Augustin-Jean Fresnel, however, favored a wave explanation and showed that refraction can be easily explained if waves change speed on entering a different medium. Their theories held sway for the coming centuries.

The 19th century seemed to finally sound the death knell of the particle theory. Firstly, Thomas Young performed his double-slit experiment showing that light could interfere, an effect that is impossible to explain using particles. (You will learn more about this important experiment later in the unit.) Christiaan Huygens developed Fresnel's wave theories to give a full explanation of this experiment from a wave perspective. Later, James Clark Maxwell developed his theories of electromagnetic waves as a special interlocked pattern of oscillating electric and magnetic fields. Furthermore, the speed of these waves was shown to be exactly the same as the speed of light, which was being measured with increasing accuracy by Armand Fizeua, Léon Foucault and Albert Michelson. Electricity and magnetism were in fact two different aspects of the same phenomenon and would become one field of study, electromagnetism. These electromagnetic waves were taken to be the final word in the description of light.

However, within 20 years Heinrich Hertz had observed that electromagnetic radiation could knock electrons off the surface of a metal plate in what came to be known as the photoelectric effect. This in itself didn't pose any problems to the wave theory of light, but after the turn of the century more detailed study of this effect by Philipp Lenard showed that the speed of the ejected electrons did not depend on the intensity of the light but its frequency. This could not be explained using Maxwell's laws and a wave view of light.

At the same time Max Planck was studying a seemingly separate problem called black body radiation. This is the radiation emitted by any hot object and cannot be fully explained using Maxwell's equations. Instead it requires the introduction of quantisation, i.e. the idea that electromagnetic energy comes in tiny packets called quanta or now more commonly photons. The energy of these photons is directly proportional to their frequency and the constant of proportion is now known as the Planck constant. The size of these packets is far too small for us to easily observe in everyday life.

In 1905 Albert Einstein applied Planck's theories to the photoelectric effect and explained why the speed of the electrons depended on the frequency of the light by considering the light as being made up of particles or photons. Interestingly, it was this, rather than his now more famous theories of relativity, for which he was awarded his first Nobel prize. However, that was 16 years later and at first his theories were not widely accepted. It wasn't until 1915 that experimental evidence from Robert Millikan and further theories from Arthur Compton and Peter Debye gave weight to Einstein's explanation of the photoelectric effect. The term 'photon' would not become widely used until a further decade later.

**Wave–particle duality**

We have seen evidence, therefore, of the particle nature of light. However, there is also evidence of the wave-like nature of light. How are we to marry these seemingly contradictory viewpoints? Modern physics now takes the view that light can act both like a wave and like a particle without contradiction. It depends on how we test it. If we look for evidence that it is a wave, we can find it. But also, if we look for evidence that it is a particle we can find that too. The universe seems to be made up of things that are both particle-like and wave-like. This is known as wave–particle duality.

It should come as no surprise, therefore, to find that objects that have traditionally been thought of as particles, e.g. electrons, can also behave like waves. Their wavelength is so small that it is not observed in everyday life, but if we can create gaps that are small enough, we can observe diffraction of electrons and other particles. Louis DeBroglie initially developed these theories in the early 20th century. Building on the work of Einstein and Planck, he was able to explain many of the mysteries of the structure of the atom, such as line spectra, which you will study later in this unit.

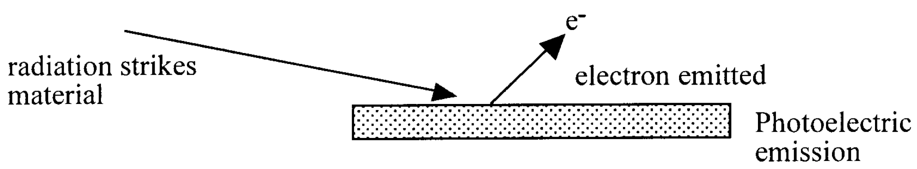
This was also the birth of quantum mechanics, heralding a massive change in how we perceive the universe. Gone was the clockwork model where, in theory, every electron, proton, atom etc. could be tracked through time as long as we had a powerful enough computer. If we measured where everything was at a certain time and what speed it was going at we could work out where it would be any time later. The modern view of the subatomic scale uses probabilities to describe both the position and speed of particles, and nothing can be known with absolute certainty. The subatomic world is a fuzzy one where little is definite.

## Photoelectric emission

Sometimes when electromagnetic radiation strikes a surface, electrons are emitted. This can be used to detect radiation and is the basis of devices such as light meters and photomultipliers. Much more importantly, however, is its place in the development of our understanding of the nature of light (and electromagnetic radiation in general).

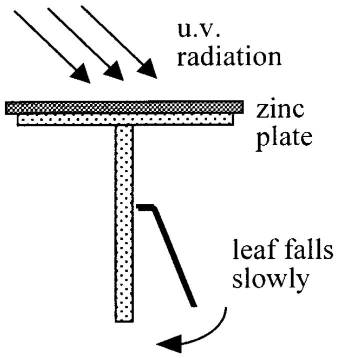
### The photoelectric effect

It is found that a negatively charged clean zinc plate loses its charge if it is illuminated with ultraviolet (UV) light. The charge is measured by the zinc plate being attached to a coulometer.



The effect *does not occur* with a *positively* charged coulometer illuminated with UV light, nor does it happen with a negatively charged coulometer illuminated by light in the visible region.

This is an example of the **photoelectric effect**.




A further observation is that UV radiation with a high irradiance causes the negatively charged coulometer to discharge more quickly.

From these results it seems that UV radiation causes electrons to be ejected (photoemission) from the zinc (since the coulometer loses *negative* charge) – the more intense the UV radiation the more electrons are ejected.

We can see that electrons are emitted if the following conditions are met:

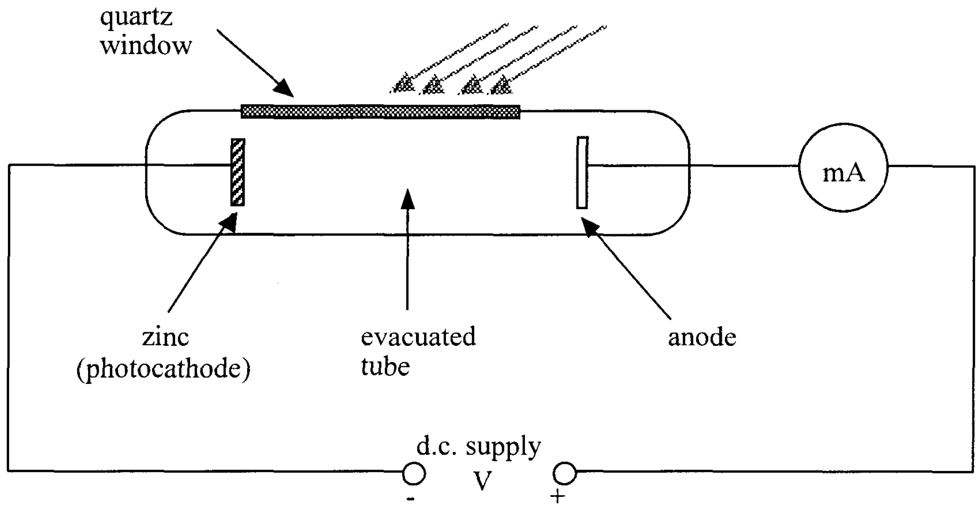
- the radiation must have a high enough frequency (or short enough wavelength)
- the surface must be suitable – the energy in UV radiation will not eject electrons from iron, copper, lead etc., but will from sodium and potassium, although these are a bit tricky to use!

*In general, the photoelectric effect is the removal of electrons from a metal surface by electromagnetic radiation.*

**Threshold frequency**

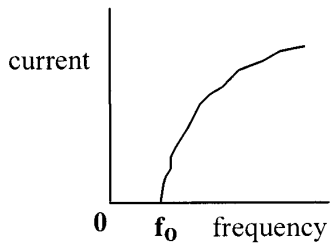
A further curious feature of photoemission is the fact that even very low irradiance UV will cause some photoemission from zinc, but very high irradiance visible light will not. The requirement for photoemission therefore depends not on the irradiance of the radiation, but on the frequency.

The following apparatus can be used to study photoemission in more detail. Rather than letting the ejected electrons escape, they are attracted to a positive plate, forming part of a circuit.



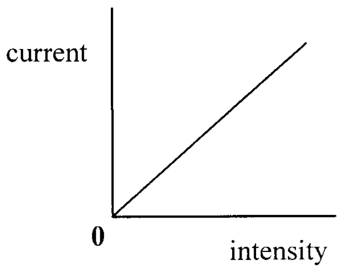

The UV radiation passes through the quartz window (a glass window would absorb the radiation) and strikes the photocathode, which is made from zinc. This causes photoelectrons to be emitted. The d.c. supply creates an electric field between the cathode and anode, which in turn causes the electrons to move across the ‘gap’ to the anode, producing a current, which is registered by a milliammeter. This is called a **photoelectric current**.

The minimum frequency that will produce photoemission from a particular surface is **threshold frequency** ($f_0$). Beyond this, an frequency will cause an increase in the speed of electrons being emitted. This in turn leads to an current. This is a square-root relationship since




called the increase in the increase in $v \propto \sqrt{E_k}$ .

It is found that the photoelectric current (i.e., the stream of electrons) is directly proportional to the intensity of the radiation:

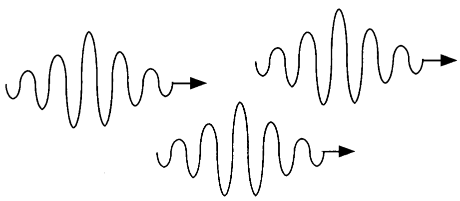


The photoelectric current is a reflection of the number of electrons emitted from the surface, so the greater the intensity of the radiation the greater the number of electrons emitted.

**Photons**

The existence of the photoelectric effect, which was discovered by Lenard in 1899, caused a problem with the wave theory of light. To eject an electron from a metal requires a precise amount of energy. A weak UV source has sufficient energy to do this for a clean zinc surface, but no matter how high the intensity of the white light is, no electrons are ejected. This is true even though, over a period of time, the 'total' energy of the white light is greater than that of the UV.

In 1904 Einstein applied an earlier idea of Planck to the phenomenon and proposed that light was not a continuous wave, but existed as a stream of 'packets' or '**quanta'**. These quanta are called **photons** and are particles of light (and other electromagnetic radiation), although unlike other particles they have no mass.



**Photons**

**Continuous wave**

Each photon still has a frequency and wavelength associated with it and the energy contained in each photon is given by:

$$E = hf$$

where $h$ is the Planck constant, $h = 6.63 \times 10^{-34}$ Js

*Note*: You do not need to know the value of this constant, it will be provided for you on the data sheet.

**Worked example**

1. What is the photon energy for red light? ($f = 4.2 \times 10^{14}$ Hz)

$E = hf$
$E = 6.63 \times 10^{-34} \times 4.2 \times 10^{14}$
$E = 2.78 \times 10^{-19}$ J

*Note*: Photons from the visible part of the electromagnetic spectrum will have energy of the order $10^{-19}$ J.

You may remember that photons are also the exchange particles for the electromagnetic force. The electromagnetic force from the light source has attracted the electrons from the metal plate through the mediation of the photon.

**Threshold frequency and work function**

As stated earlier, it is found that for a particular metal there is a minimum frequency of radiation required in order to eject an electron from it. Photons at or above this threshold frequency will eject electrons; those with less than this frequency will not. Clearly therefore there is a **threshold energy**, i.e. the energy that photons must have if they are to eject electrons.

This threshold energy is called the **work function** for the surface:

$$\text{work function} = hf_0$$

An electron released by a photon having this level of energy will have absorbed sufficient energy to escape but will have no energy 'left over', i.e. it will have zero kinetic energy.

If the energy of the incident photon is greater than the work function, the 'extra' energy will appear as kinetic energy of the electron, so:

$$E_k = hf - hf_0$$

total energy of photon ($hf$)

energy required to remove electron ($hf_0$)

*Note*: The energy transferred to the electrons depends *only on the frequency of the photons*. Higher irradiance radiation does not increase the velocity of the electrons; it produces more electrons of the same velocity.

**Worked example**

The work function of a cesium metal surface is $2.16 \times 10^{-19}$ J.

(a) Calculate the minimum frequency of radiation that will emit photoelectrons from this metal.

(b) If light of wavelength 589 nm is incident on the surface, calculate the maximum kinetic energy gained by each photoelectron.

(c) Hence calculate the maximum velocity with which photoelectrons will be emitted from the surface.

($h = 6.63 \times 10^{-34}$ Js; mass of an electron = $9.11 \times 10^{-31}$ kg)

(a)

$$\text{work function} = hf_0 = 2.16 \times 10^{-19}$$

$$f_0 = \frac{2.16 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$= 3.26 \times 10^{14} \text{ Hz}$$

(b)

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8}{589 \times 10^{-9}}$$

$$= 5.09 \times 10^{14} \text{ Hz}$$

$$E_k = hf - hf_0$$

$$= 6.63 \times 10^{-34} \times 5.09 \times 10^{14} - 2.16 \times 10^{-19}$$

$$= 3.37 \times 10^{-19} - 2.16 \times 10^{-19}$$

$$= 1.21 \times 10^{-19} \text{ J}$$

(c)

$$\frac{mv^2}{2} = 1.21 \times 10^{-19}$$

$$v^2 = \frac{2 \times 1.21 \times 10^{-19}}{9.11 \times 10^{-31}}$$

$$= 2.66 \times 10^{11}$$

$$v = 5.15 \times 10^5 \text{ ms}^{-1}$$

*Note*: Remember, electron velocities should not exceed the speed of light!

## Irradiance and the inverse square law

### What is irradiance?

Irradiance of radiation is a measure of the radiation falling on a surface. It is defined as the energy falling on a surface per unit time (i.e. the power per unit area). This relationship can be summarised:

$$I = \frac{P}{A}$$

$I$ = irradiance in W $m^{-2}$

$P$ = power in watts

$A$ = area in $m^2$

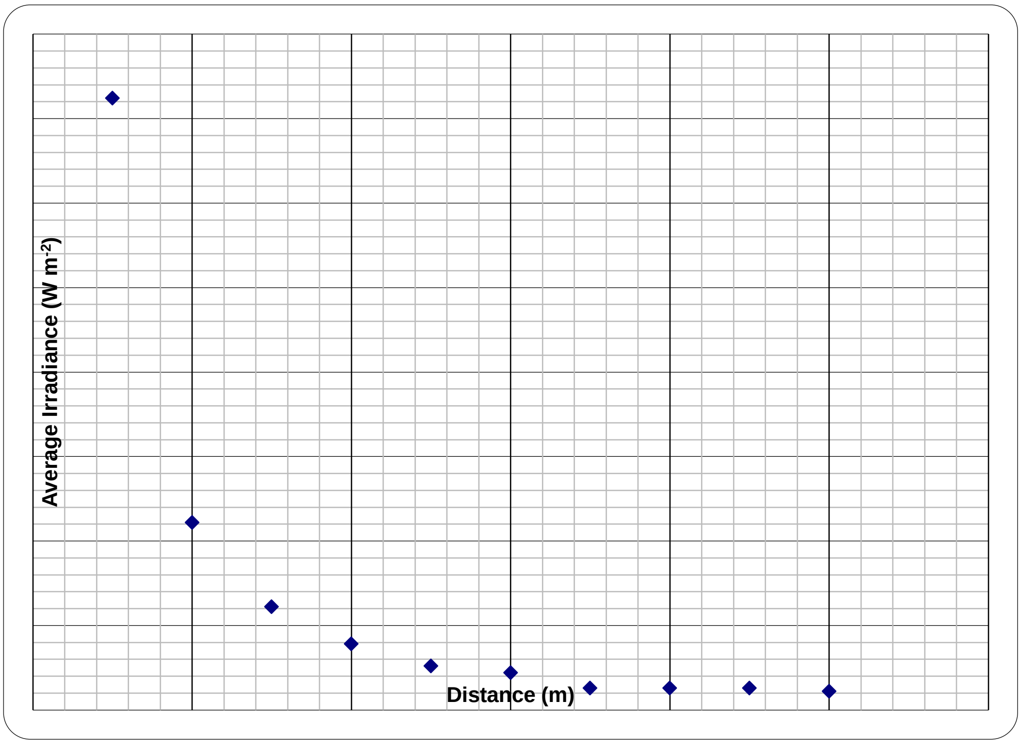
### Why does irradiance matter?

An understanding of irradiance is relevant to a range of applications. For example, NASA monitors solar irradiance to understand the activity of the Sun and climate scientists study solar irradiance to research the impact of solar activity on the Earth's climate. Interactions between solar radiation and the atmosphere of the Earth can impact on air quality, and understanding of irradiance can allow investigation of the composition of the Earth's atmosphere. Excessive exposure to sunlight has been linked to the development of a range of skin cancers. The performance of solar cells, an increasingly common use of solar radiation as an energy resource, requires an understanding of irradiance.

### Investigating irradiance

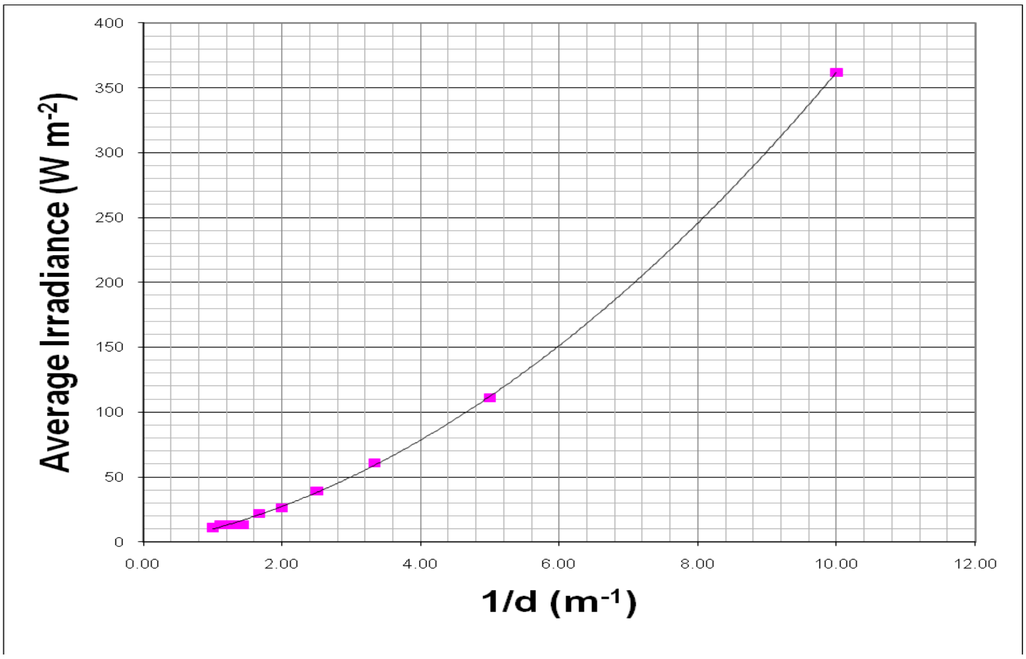
The relationship between irradiance of a point source and the distance from that source can be investigated using a simple experimental set up: a light source and a linear light meter.

The graph of a typical set of results from such an experiment is shown below:

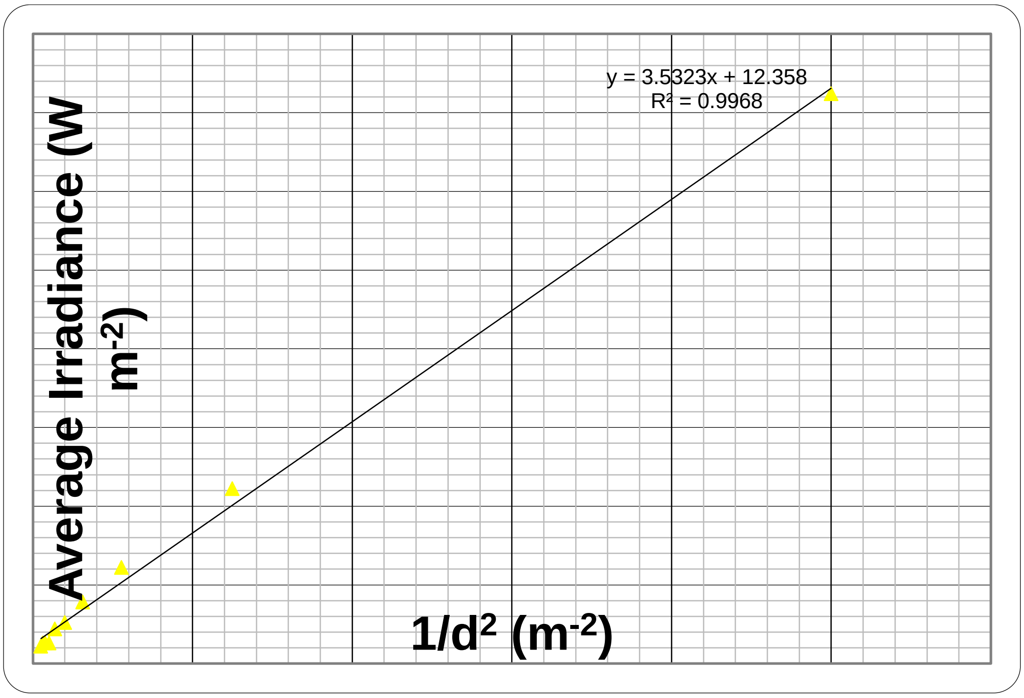



It is clear from this graph that the relationship between irradiance and distance is not a linear one.

Graphing average irradiance against 1/*d* (*d* = distance) demonstrates that average irradiance is not proportional to 1/*d*.




The graph of average irradiance against $1/d^2$ demonstrates a linear relationship.



From the graph:

$$I \propto \frac{1}{d^2}$$
$$Id^2 = \text{constant}$$
$$I_1 d_1^2 = I_2 d_2^2$$

$I$ = irradiance in W m$^{-2}$

$d$ = the distance from a point source in m

This is described as an inverse square law.

A point source is one which irradiates equally in all directions, i.e. the volume that will be irradiated will be a sphere. The surface area of a sphere can be calculated using $A = 4\pi r^2$, i.e. the area which will be irradiated is proportional to $r^2$ (or $d^2$).

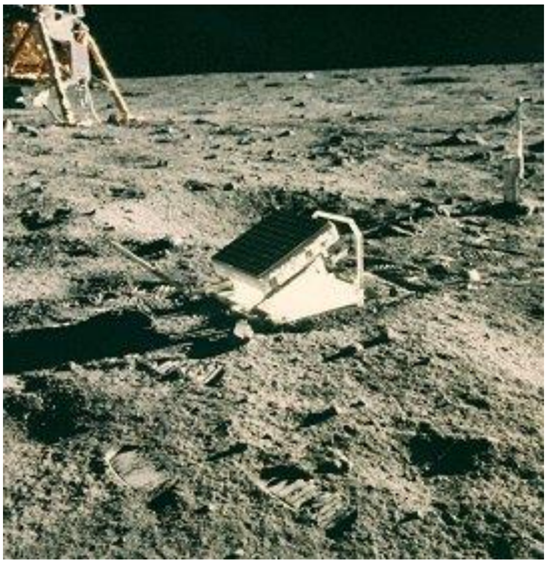
**Calculating solar irradiance and the power of the Sun: measuring a sunbeam**

Watch the clip from ‘Measuring a sunbeam’ (BBC Wonders of the Solar System episode ‘Empire of the Sun’ at http://www.bbc.co.uk/programmes/p006szxm.

Professor Brian Cox uses a simple technique to measure the solar energy falling on the Earth, recreating an experiment first carried out by Sir John Herschel in 1838. Pause the clip and use your understanding of irradiance to make the calculations on the Sun’s irradiance.

**Irradiance and the distance to the moon**

When Neil Armstrong and Buzz Aldrin walked on the surface of the moon on 21 July 1969 as part of the Apollo mission, they set up a lunar laser ranging reflector array, a 0.6 m panel with 100 mirrors. This is the only experiment from the successful Apollo 11 mission that is still running.



The Apollo 11 lunar laser-ranging retro reflector array © NASA.

A laser pulse is transmitted from a telescope on Earth. The reflectors in the array are designed to send the pulse back precisely to the location from which it was transmitted. Telescopes on Earth receive the returned pulse.

For more than three decades it was possible to use this technique to make observations of the moon's orbit, the universal gravitational constant, the composition of the moon, and whether Einstein's theory of relativity works in practice.

Measuring the time for the pulse to be returned allows the moon's distance to be calculated very precisely. Until 2005 the measurements allowed calculation to within a few centimetres, a very small uncertainty for a distance of approximately 385 000 000 m! The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO for short) in New Mexico, which came online in 2005, allows these measurements to be made to within a few millimetres.

Among its aims, the APOLLO project will measure the $1/r^2$ law (i.e. the inverse square law) at the lunar distance scale, i.e. approximately $10^{12}$ m.

What makes a laser suitable for these types of experiment over astronomical distances? A laser has a very small beam divergence over a distance, compared with a light source such as an ordinary filament lamp. Nevertheless, the laser beam is approximately 7 km in diameter by the time it reaches the moon.

### Irradiance and the electromagnetic spectrum

The inverse square law applies to all electromagnetic radiation, i.e. to visible light and all wavelengths on the electromagnetic spectrum, from radio waves to gamma rays.

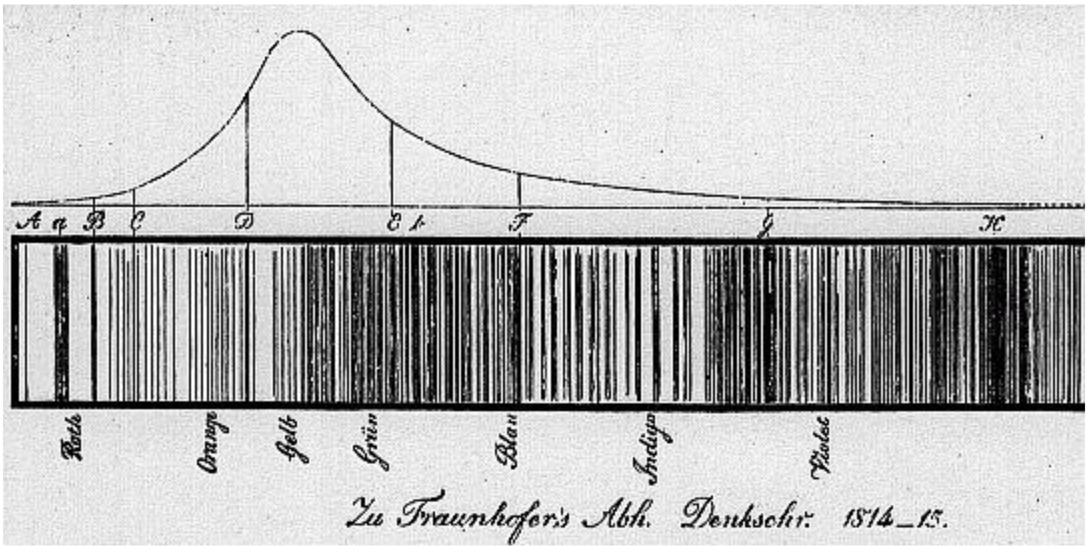
## A model of the atom and the electromagnetic spectrum

Vibrating charges produce radiation. This is the source of electromagnetic radiation, e.g. visible light, X-rays and gamma rays.

At the end of the 19th century, physicists knew that atoms contained electrons and the motion of these electrons resulted in electromagnetic radiation. However, a mystery remained. Solving this mystery, and the work of scientists including Fraunhofer, Brewster, Kirchoff, Bunsen and Ångstrom, took forward a new area of science – spectroscopy – which revolutionised solar physics and astronomy.

Prior to Isaac Newton's prism experiment in 1666, the nature of celestial bodies such as the Sun and stars was not well understood. The luminescence from such bodies was attributed to an 'essence'.

In 1802 William Wallaston observed lines in the spectrum from the Sun. The systematic study of these lines was undertaken by a German optician, Joseph Fraunhofer.






*This is a reproduction of Fraunhofer's original 1817 drawing of the solar spectrum. The more prominent dark lines are labelled alphabetically; some of this nomenclature has survived to this day*

In the 1850s Kirchoff (a German physicist, 1824–1887) and Bunsen (a German chemist, 1811–1899) took another step forward in spectroscopy with the discovery that when various substances were held in the flame of a Bunsen burner and the light produced passed through a prism, distinct spectra were seen, which correspond to distinct elements in the substance. You may have carried out similar experiments in science at school, for example burning a copper salt in a Bunsen flame and observing the distinctive green colour, or sodium (yellow flame), or potassium (lilac flame), or calcium (red flame).

In the 1860s this technique was used by Kirchoff and Bunsen to discover two new elements, caesium and rubidium. Other elements that were discovered using this approach were gallium, helium, argon, neon, krypton and xenon.

We can use a spectroscope to observe various light sources around you, e.g. daylight (do not point the spectroscope directly at the Sun) and the artificial lighting within the classroom If you do not have a spectroscope in school, it is possible to build a simple one that works just as effectively (http://www.exploratorium.edu/spectroscope/).

A spectrophotometer allows you to observe and record data of the spectrum for a range of light sources. You can compare the spectrum of an ordinary filament lamp with time from its first switch-on. Compare this with the spectrum of an ordinary filament lamp with differing voltage across the lamp. Also contrast these with the spectrum of an energy-saving lamp with time.

**Max Planck and the quantisation of energy**

In 1900 the German physicist Max Planck (1858–1947; Nobel Prize winner 1918) proposed the quantisation of the energy of a vibrating molecule, i.e. it could only take on certain fixed values.

This helped to explain the gaps and lines in the spectra of elements.

He proposed that:

$$E \propto f$$

with a constant of proportionality $6.626 \times 10^{-34}$ J s, this came to be known as Planck's constant (h).

| | |
|---|---|
| $E = hf$ | $E$ = energy in joules (J)<br>$f$ = the frequency in hertz (Hz)<br>$h$ = Planck's constant = $6.626 \times 10^{-34}$ J s |

This was a revolutionary idea which provided the basis for quantum physics. Einstein built on Planck's work, proposing that light was also quantised in photons.

## The Bohr model of the atom

In 1911–1913 the Danish physicist Neils Bohr (1885–1962; Nobel Prize winner 1922) collaborated in Cambridge and Manchester with JJ Thomson and Ernst Rutherford.

Bohr knew that a charged body in motion must emit energy as electromagnetic radiation.

This meant that orbiting electrons should emit energy, as a result lose energy and spiral into the nucleus of the atom. This would suggest that the atom cannot be stable.

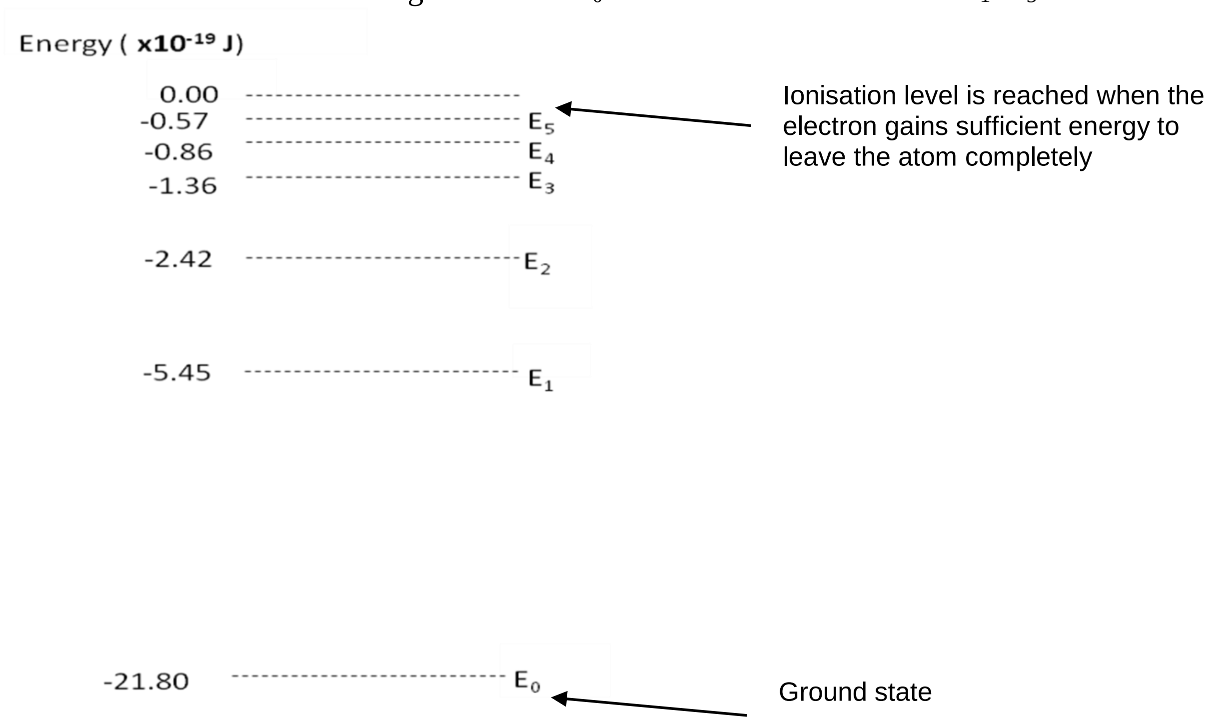
Bohr struggled to reconcile the accepted model of the atom with this conclusion.
In 1913, Bohr proposed a new model of the atom, which was recognised with the award of the Nobel prize for physics in 1922, and (with some further improvement to take account of Heisenberg's work in the 1920s), remains the model that accounts for the physical and chemical properties of elements today.

In the Bohr model:

- Electrons exist only in allowed orbits. An electron in an allowed orbit does not radiate energy, i.e. Bohr's model proposed that the classical electromagnetic theory was incorrect. Electrons can jump between allowed states, and this jump is associated with absorption or emission of electromagnetic radiation.
- Electrons in different orbits have different energies, thus these orbits can be considered energy levels.
- Electrons tend to occupy the lowest available energy level, i.e. the level closest to the nucleus.

The allowed orbits of electrons can be represented in an energy level diagram. The diagram below represents the energy levels within a hydrogen atom.

Electrons can exist either in the ground state $E_0$ or in various excited states $E_1$–$E_5$.




An electron in an excited state can make a transition into a lower energy state.

In a hydrogen atom, the possible transitions are:

E1 → E0, E2 → E0, E3 → E0, E4 → E0, E5 → E0
E2 → E1, E3 → E1, E4 → E1, E5 → E1
E3 → E2, E4 → E2, E5 → E2
E4 → E3, E5 → E3
E5 → E4

When an electron makes a transition from a higher energy state to a lower energy state where does the excess energy go? It is emitted as a photon of electromagnetic radiation. In the Bohr model, it follows that the possible excess energies must be quantised, i.e. in specific 'packets', since the electron can make transitions only between specified energy levels.

The frequency of the emitted radiation is proportional to the difference in the energy levels ($\Delta E$):

$$\Delta E \propto f$$

It follows that since $\Delta E$ is quantised, the photons emitted can only be of specified frequency.

## The Bohr model and spectra

This theory applies only to **free atoms**. A free atom is one that is not affected by neighbouring atoms, as in a gas. In sources such as filament lamps, the atoms are not free and their electrons may be shared in bonding with other atoms. This results in an infinite number of possible transitions, giving an infinite number of lines, i.e. a continuous spectrum.