Edexcel Physics A-level

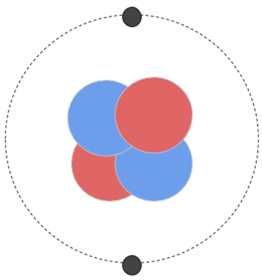
Topic 8: Nuclear and Particle Physics

Notes

8 - Nuclear and Particle Physics

8.130 - Nucleon number and proton number

An atom is formed of 3 constituents: **protons, neutrons and electrons**. At the centre of an atom is a nucleus formed of protons and neutrons, therefore they are known as nucleons, whereas electrons orbit the nucleus in shells.

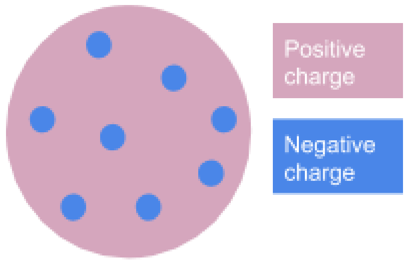


The **proton number** is the number of protons in an atom and is denoted by Z, while the **nucleon number** is the number of protons and neutrons, denoted by A. These will often be shown in the form: (where 'X' is the symbol for the element).

$$^{A}_{Z}X$$

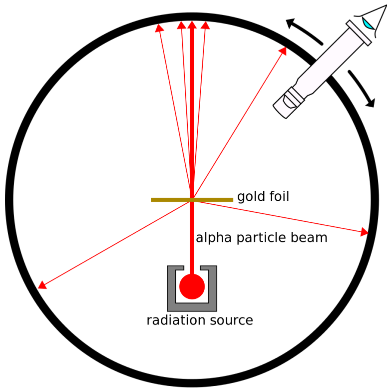
8.131 - Alpha particle scattering as evidence for the nuclear model of the atom

Rutherford scattering demonstrated the existence of a nucleus. Before this experiment, scientists believed in **Thomson's plum pudding model** which stated that the atom was made up of a sphere of positive charge, with small areas of negative charge evenly distributed throughout like plums in a plum pudding. Rutherford scattering led to the production of a new model for the atom, known as the **nuclear model** because the plum pudding model had been disproved.



Plum pudding model

Rutherford's apparatus included an **alpha source and gold foil in an evacuated chamber which was covered in a fluorescent coating**, which meant you could see where the alpha particles hit the inside of the chamber. To observe the path of the alpha particles, there was a **microscope** which could be moved around the outside of the chamber.



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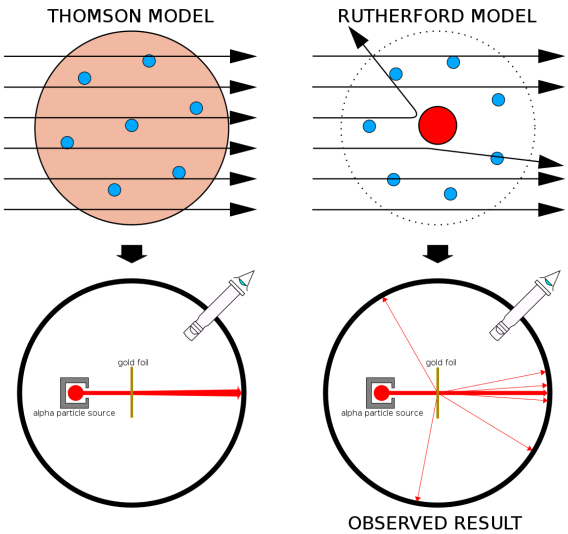
If the plum pudding model was true, the expected results would be that the positively charged alpha particles would be deflected by a very small amount when passing through the foil, however this was not what was observed:

- **Most alpha particles passed straight through the foil with no deflection** - this suggested that the **atom is mostly empty space** (and not a uniform density as suggested by the plum pudding model).
- **A small amount of particles were deflected by a large angle** - this suggested that the **centre of the atom is positively charged**, as positively charged alpha particles were repelled from the centre and deflected.
- **Very few particles were deflected back by more than 90°** - this suggested that the **centre of the atom was very dense** as it could deflect fast moving alpha particles, but also that it was **very small** as a very small amount of particles were deflected by this amount.

From the above results it was concluded that the atom has a small, dense, positively charged **nucleus** at its centre.



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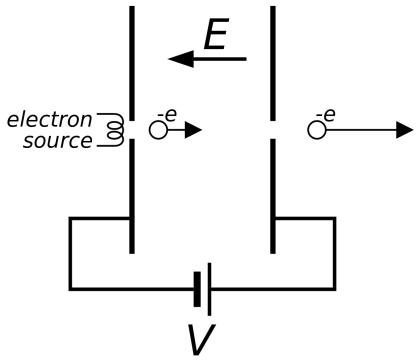
8.132 - Thermionic emission

Thermionic emission is where a metal is heated until the free electrons on its surface gain enough energy and are emitted.

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

Electron guns use a potential difference in order to accelerate electrons, which are released from the cathode by heating it **(thermionic emission)**. The electrons are **accelerated towards the anode**, which has a small gap, the electrons which pass through this gap form a narrow electron beam which travels at a constant velocity beyond the anode.

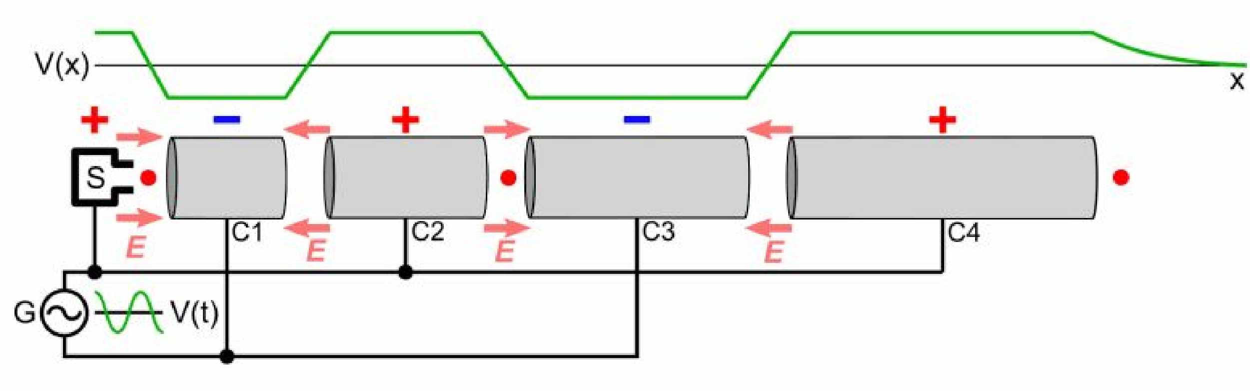


8.133 - Particle accelerators and detectors

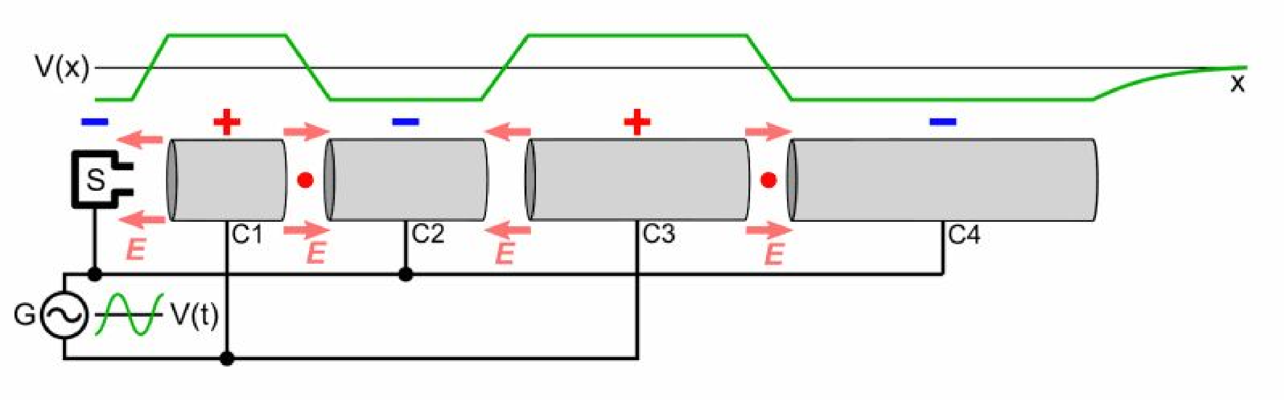
Electron guns are useful for producing electron beams of a relatively low energy to be used in particle accelerators. There are two types of particle accelerators that you need to be aware of:

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

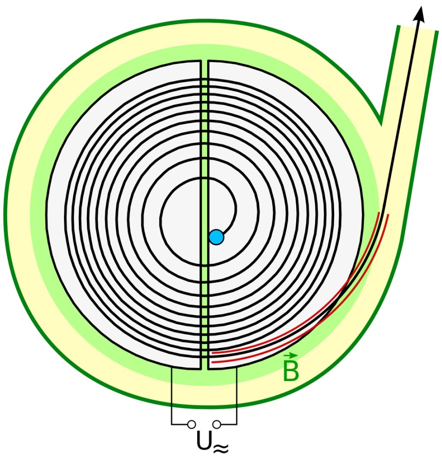
Linear accelerators are formed by several cylindrical electrodes, called drift tubes, which progressively increase in length along the accelerator (labelled C1 - C4 in the diagram below). Adjacent electrodes are connected to the opposite polarity of an alternating voltage, which means that alternating electric fields are formed in the gaps between electrodes.



At the particle source (labelled S), groups of charged particles are released such that the polarity of the voltage of the first electrode is opposite to the polarity of the charged particles, so that they are **accelerated** towards the first electrode. The length of the cylindrical electrodes is calculated such that, just as the particle passes through the electrode, the polarity of the voltage (and so the electric field) reverses, meaning that the particles can be **accelerated** towards the next electrode. And this process repeats until the particles reach the desired speed.



A cyclotron is formed of **two semi-circular electrodes** called "Dees", with a **uniform magnetic field** acting **perpendicular** to the plane of the electrodes, and a high frequency **alternating voltage** applied between the electrodes. The charged particles move from the **centre** of one of the electrodes, and are deflected in a circular path by the magnetic field. (Because the force exerted by the magnetic field is always perpendicular to the direction of travel, the particle's speed will not increase due to the magnetic field, which is why there is an alternating electric field between the electrodes).

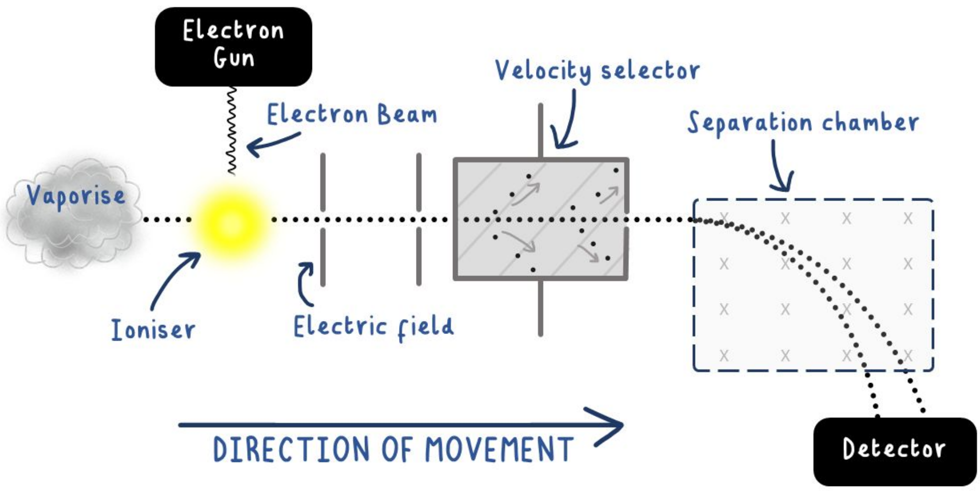


Once the particles reach the edge of the electrode they begin to move across the gap between the electrodes, where they are **accelerated by the electric field**, meaning the **radius of their circular path will increase** as they move through the second electrode. When the particles reach the gap again, the **alternating electric field changes direction, allowing the particles to be accelerated again**. This process repeats several times until the required speed is reached by the particles and they exit the cyclotron.

Electric and magnetic fields are also used in **particle detectors**, such as mass spectrometers, which work in the following way:

1. A sample is vaporised, meaning it is converted into a vapour (gas)
2. Next, an **electron gun** is used to create a beam of electrons which are directed at the vapour. The fast-moving electrons collide with the ions in the vapour causing them to become **ionised** (lose electrons), causing them to become charged.
3. Then, the ions are accelerated using an **electric field** as they are now charged.
4. Once they have been accelerated, they pass into the **velocity selector**, where an electric and magnetic field are acting perpendicular to each other. The fields exert forces on the ions in opposite directions and only the ions for which the **forces are balanced** travel in a straight line and then pass through into the separation chamber. This results in only particles travelling at a particular speed progressing into the next part of the mass spectrometer.
5. In the separation chamber, there is a uniform magnetic field which exerts a force on the ions **perpendicular** to their direction of travel, causing them to follow a **circular path** and hit a screen, where the radius of their circular path can be measured.

The radius of the path of the ions is used to determine their **mass-to-charge ratios**, which are used to identify the sample.



8.134 - Radius of the path for a charged particle in a magnetic field

The force exerted by a magnetic field on a charged particle is always perpendicular to its motion of travel, which causes charged particles to follow a **circular path** when in a magnetic field, because the force induced by the magnetic field acts as a **centripetal force**.

By combining the formulas for centripetal force and magnetic force on a charged particle, you can derive the formula to find the radius of the particle's circular path:

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

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

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

You can simplify the equation above further by using the fact: p = mv

$$r = \frac{p}{BQ}$$

Where **p** is the particle's momentum, **Q** is its charge and **B** is the magnetic flux density.

8.135 - Applications of conservation laws

During particle interactions, the following properties must **always** be conserved:

- **Charge**
- **Energy**
- **Momentum**

To show that the above properties are conserved in a particle interaction, you must find the value of each property before and after the interaction and make sure they are **equal**.
For example, beta-minus decay:

$$n \rightarrow p + e^{-} + \overline{\nu}_e$$

	Charge	Explanation
Before interaction	0	A neutron has no charge.
After interaction	1-1+0=0	The charge of a proton is +1, an electron is -1 and an electron antineutrino is 0. These sum to 0.
Change	0	The charge is conserved as required.

You can observe the movement of **charged particles** by looking at the particle tracks from a cloud or bubble chamber. Both of these devices rely on the fact that charged particles leave a trail of ionised particles in their path, and these ionised particles can be detected.

A **bubble chamber** is formed of a tank filled with superheated liquid hydrogen, which forms bubbles around any ionised particles created as a result of the movement of a **charged particle**. Therefore, by observing the path created by these visible bubbles you can see the path taken by moving, charged particles. As the tank is placed in a **magnetic field**, charged particles can be seen to take circular paths.

Image source: Rice University, CC BY 4.0

You can analyse bubble chamber tracks in the following ways:

- ➔ **Find the radius of curvature of tracks** - this will allow you to find out certain characteristics of the particle you are observing by using the following equation (which is derived above):

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

- ➔ **Find the direction of curvature** - this will allow you to find out whether a particle has a positive or negative charge by using Fleming's left hand rule *(covered in topic 7.122)*.
- ➔ **Analyse interactions** - you see what particle interactions occur by looking at the shape of particle tracks:
  - ◆ If the tracks **stop suddenly** - particles have **collided**
  - ◆ If the tracks abruptly **change direction** - particles have **collided**
  - ◆ If the tracks look like they **have come from nothing** (as seen in the red and blue tracks highlighted below) - particles have been **created** from an **uncharged particle** (photon) which doesn't create tracks in a bubble chamber

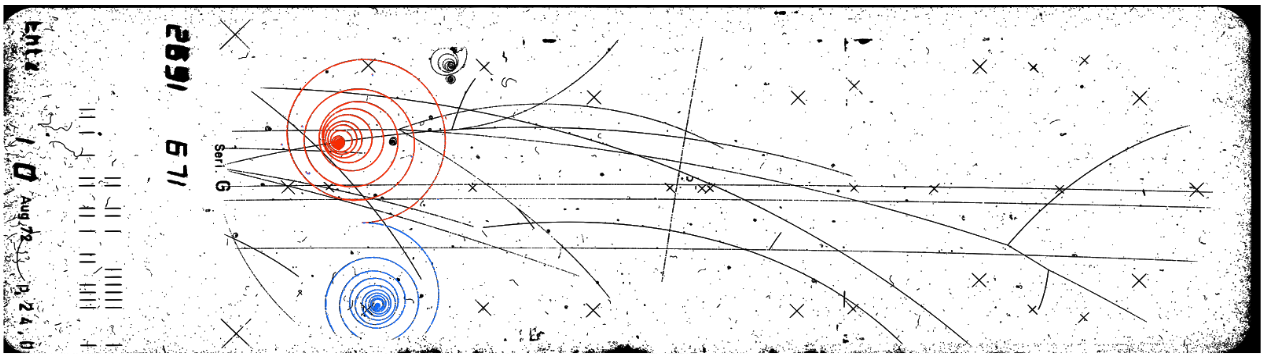


Image source: CERN

8.136 - Investigating the structure of nucleons

When investigating an object, you **must** use waves with a wavelength similar in size to that of the object you are investigating. You can find the wavelength of particles by using the de Broglie relation, which shows that a particle's momentum and wavelength are inversely proportional:

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

Where **λ** is the de Broglie wavelength, **h** is the Planck constant and **p** is the momentum of the particle.

By looking at the De Broglie relation, you can see that the smaller the de Broglie wavelength needed, the higher the energy (/momentum) of the particle required.

Nucleons are incredibly small, around 1.6 fm (10^{-15})! Because of this, you must use **very small wavelengths** when investigating them, meaning the particles you use will have **extremely high energies**.

8.137 - Creation and annihilation of matter and antimatter particles

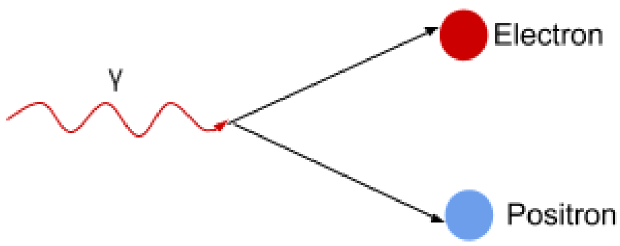
In the theory of special relativity Einstein proved that mass and energy are interchangeable and can be related by the following equation:

$$\Delta E = \Delta mc^2$$

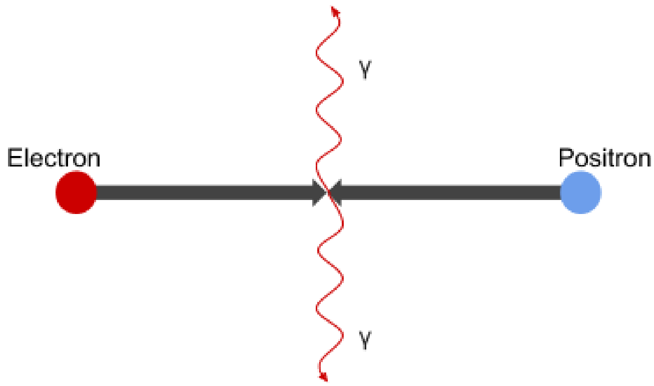
Where **E** is energy, **m** is mass and **c** is the speed of light in a vacuum.

This means that at any time, **mass and energy can be exchanged**. This can be seen through the following processes which occur at the subatomic scale:

Pair production is where a photon is converted into an equal amount of matter and antimatter. This can only occur when the photon has an energy greater than the total rest energy of both particles, any excess energy is converted into the kinetic energy of the particles.



Annihilation is where a particle and its corresponding antiparticle collide, as a result their masses are converted into energy. This energy, along with the kinetic energy of the two particles is released in the form of 2 photons moving in opposite directions in order to conserve momentum.



8.138 - eV as units for energy and eV/c² as units for mass

The **electronvolt (eV)** is a unit of energy, usually used to express small energies. 1 eV is equal to the kinetic energy of an electron accelerated across a potential difference of 1 V or 1.6×10^{-19} J.

To express the amount of energy present in particle interactions, it is usually more useful to use:

- **MeV** (Megaelectronvolts) - this is equivalent to $\mathbf{1.6 \times 10^{-13}}$ **J**
- **GeV** (Gigaelectronvolts) - this is equivalent to $\mathbf{1.6 \times 10^{-10}}$ **J**

You can convert **from joules to MeV or GeV** by **dividing** the value by either 1.6×10^{-13} J (for MeV) or 1.6×10^{-10} J (for GeV).
You can convert **from MeV or GeV to joules** by **multiplying** the value by either 1.6×10^{-13} J (for MeV) or 1.6×10^{-10} J (for GeV).

By rearranging the mass-energy equivalence formula so that mass is the subject, you can see that mass can have the units **j/c²** (where the units of c have not been simplified further).

$$E = mc^2$$

$$m = \frac{E}{c^2}$$

If you are using MeV or GeV as the units of energy instead of joules, the **unit of mass** would become: **MeV/c²** or **GeV/c²**.

You can convert **from kg to MeV/c² or GeV/c²** by **dividing** the value by either 1.6×10^{-13} J (for MeV) or 1.6×10^{-10} J (for GeV) and then **multiplying** it by **c²** ($9 \times 10^{16}\ m^2s^{-4}$).

- ➔ This is equivalent to **just multiplying** by 5.625×10^{29} (for MeV/c²) or 5.625×10^{26} (for GeV/c²).

You can convert **from MeV/c² or GeV/c² to kg** by **multiplying** the value by either 1.6×10^{-13} J (for MeV) or 1.6×10^{-10} J (for GeV)and then **dividing** it by **c²** ($9 \times 10^{16}\ m^2s^{-4}$).

- ➔ This is equivalent to **just multiplying** by $8/45 \times 10^{-29}$ (for MeV/c²) or $8/45 \times 10^{-26}$ (for GeV/c²).

8.139 - Relativistic increase in particle lifetimes

When particles are travelling at speeds that are comparable to the speed of light (**relativistic speeds**), some of their properties appear to change. One of these properties is the length of their lifetimes, this is due to a process known as **time dilation**, which occurs as a consequence of special relativity. Time dilation causes time to run at different speeds depending on the motion of an observer.

As a consequence of time dilation, the lifetime of a particle moving at relativistic speeds recorded by a stationary observer would be **longer** than the actual time (as suggested by predictions).

Muon decay provides **experimental evidence** for time dilation because muons enter the atmosphere at very high speeds and so experience significant time dilation, which affects how quickly they decay. Muons are formed in the upper atmosphere and have a lifetime of around **2 μs**, which suggests that as they travel to the surface of the Earth, most would decay before reaching sea level, however experimental evidence showed the opposite to be true. Most muons (around 80%) were still present upon reaching sea level, even though more than 2 μs had passed to an external observer. This can only be explained by time dilation as the muons are travelling at close to the speed of light.

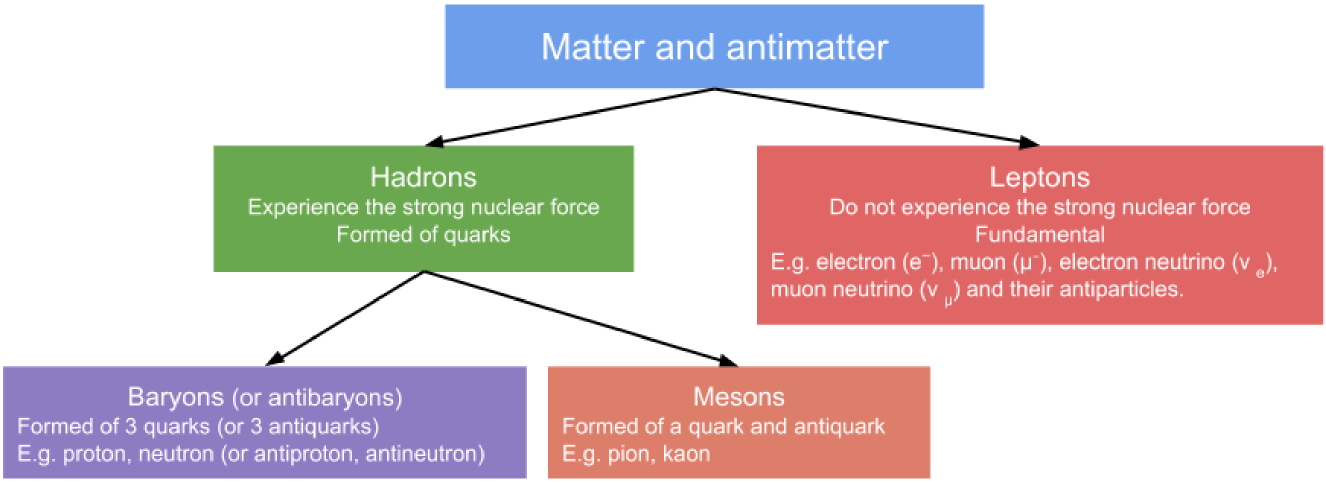
Time dilation also occurs in the context of **accelerator collision experiments** as particles are moving are speeds comparable to the speed of light. This means that their lifetimes (as observed by a stationary observer) are **longer** so particles travel for longer than expected (when taking their usual lifetimes into account) and so can interact with more particles.

8.140 - The standard quark-lepton model

All particles can be classified as either **hadrons**, **leptons** or **photons**. The differentiating property between hadrons and leptons is that leptons are fundamental particles, meaning they cannot be broken down any further, also they **do not** experience the strong nuclear force (one of the four fundamental forces). On the other hand, hadrons are formed of **quarks** (quarks are fundamental particles), and hadrons experience the strong nuclear force. Whereas photons are the fundamental particles which make up light.

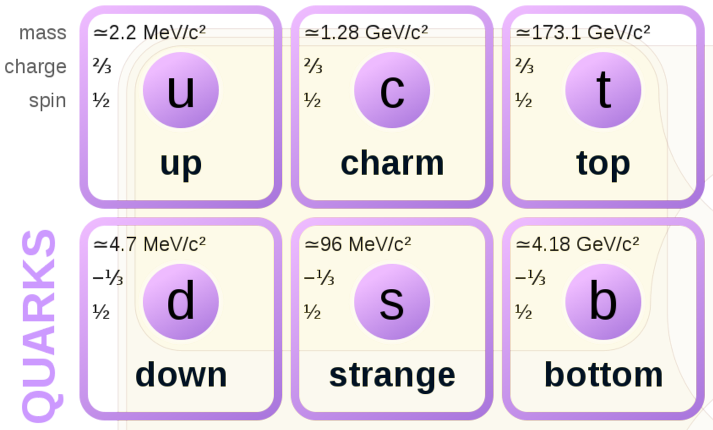
Hadrons can be further separated into baryons, antibaryons and mesons. **Baryons** are formed of 3 quarks, **antibaryons** are formed of 3 antiquarks while **mesons** are formed from a quark and antiquark.

The classification of matter and antimatter is summarised below:



In the standard model there are 6 types of quarks:

- Up, down, charm, strange, top and bottom (as shown below).



The **top quark** was predicted by the symmetry of the standard model, which implied that there existed a particle which had yet to be observed. Due to the symmetry of the model, experiments were carried out and the top quark was finally discovered.

8.141 - Particles and antiparticles

For **every** type of particle there is an **antiparticle** which has the same rest energy and mass but all its other properties are the **opposite** to the particle's. For example, the positron is the antiparticle of the electron, and an electron antineutrino is the antiparticle of a neutrino; this is how their properties compare:

Particle	Mass (kg)	Rest energy (Mev)	Charge (C)
Electron (e^-)	9.11×10^{-31}	0.511	-1.6×10^{-19}
Positron (e^+)	9.11×10^{-31}	0.511	$+1.6 \times 10^{-19}$
Electron neutrino (ν_e)		0	0
Electron antineutrino ($\overline{\nu_e}$)		0	0

8.142 - Determining whether particle interactions are possible

A particle interaction is **only** possible if **all** conversation laws are obeyed. Along with the conversation of energy and momentum, the following properties must be conserved in a particle interaction:

- **Charge**
- **Baryon number** - this shows whether a particle is a baryon (its baryon number is 1), antibaryon (-1) or not a baryon (0).
- **Lepton number** - this shows whether it is a lepton (its lepton number is 1), antilepton (-1) or not a lepton (0).

To show that these properties are obeyed in an interaction, you must find the value of each property before and after the interaction and make sure they are equal.

As an example consider this particle interaction,

$$p \longrightarrow n + e^+ + \upsilon_e$$

	Charge	Baryon number	Lepton number	Explanation
Before interaction	1	1	0	The proton has a charge of +1. As a proton is a baryon, it has a baryon number of +1 and lepton number of 0.
After interaction	0+1+0=1	1+0+0=1	0+1-1=0	The positron (e^+) has a charge of +1, while the neutron and electron neutrino have no charge. As the neutron is a baryon it has a baryon number of +1. The positron is an antilepton so has a lepton number of -1, while the neutrino is a lepton so has a lepton number of +1.
Change	0	0	0	Charge, baryon number, and lepton number are conserved.

All the above conservation laws are obeyed therefore this interaction is possible.

8.143 - Particle equations

You must be able to **write** and **interpret** particle equations given the relevant particle symbols. For example, the following equation shows the **alpha decay** *(discussed in topic 11)* of uranium (U) into thorium (Th) and an alpha particle (α):

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$$

You can check whether the interaction above is possible by considering the charge, baryon number and lepton number before and after the interaction.

	Charge	Baryon number	Lepton number
Before interaction	92	238	0
After interaction	90+2=92	234+4=238	0
Change	0	0	0

As the conservation laws are obeyed, this interaction is **possible**.