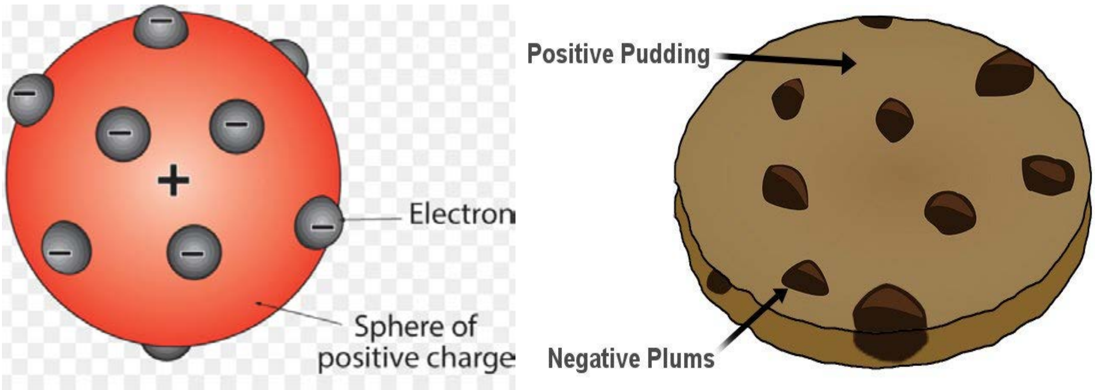
OCR A Physics A-level

Topic 6.4: Nuclear and Particle Physics

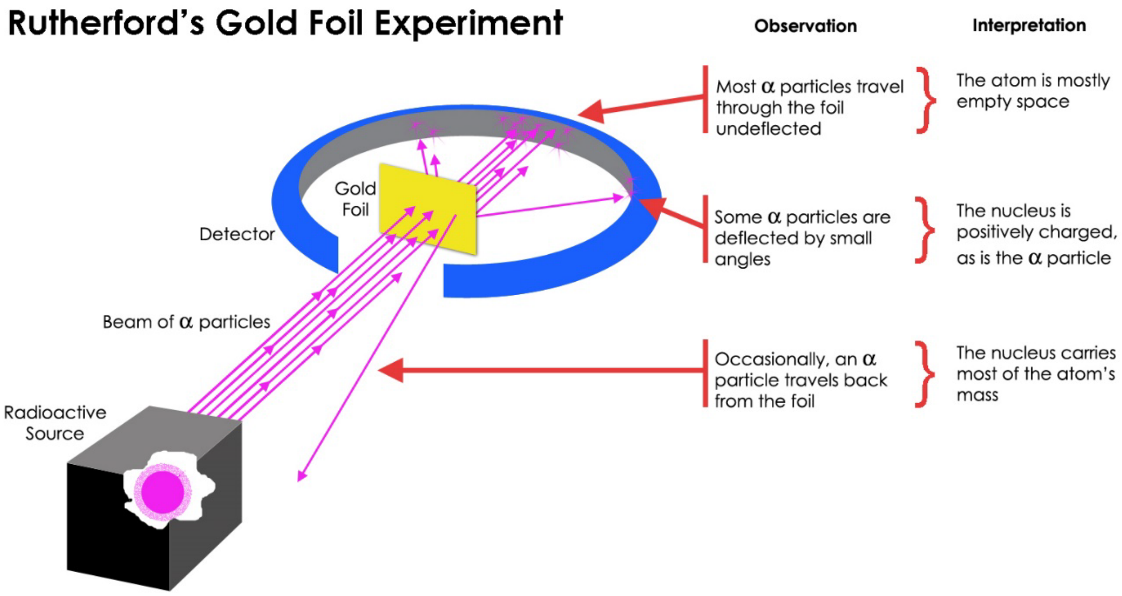
(Content in italics is not mentioned specifically in the course specification but is nevertheless topical, relevant and possibly examinable)

Rutherford's Alpha-Particle Scattering Experiment

After the discovery of the electron by Thompson, a model for the atom was proposed in which a neutral atom is made up of a uniform sphere of positive charge with tiny electrons embedded in it like the fruit in a plum pudding, hence the name the Thompson's 'Plum Pudding Model'.

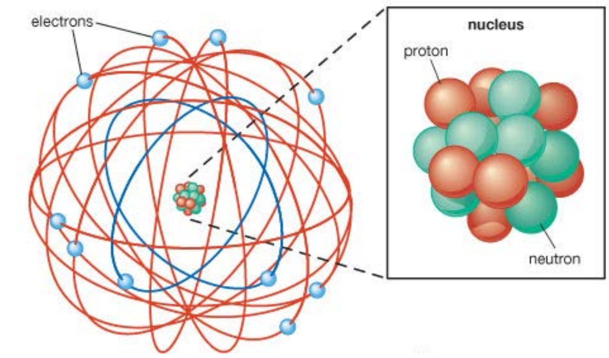


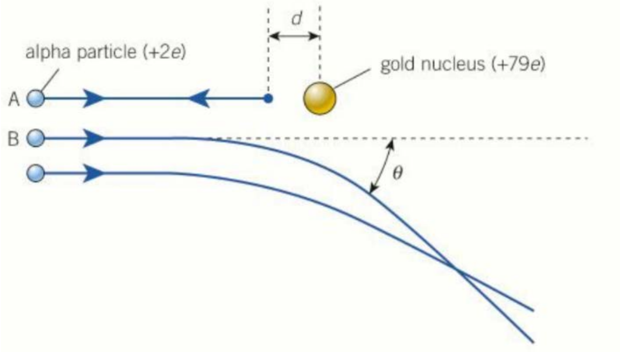
Rutherford's alpha-scattering experiment disproved this model. In the experiment, alpha particles were fired at a thin sheet gold foil (approximately 400 atoms thick) under a vacuum (the vacuum was necessary so that the particles alpha particles were not stopped by air in the apparatus). The deflected alpha particles were detected on all sides by a ring of scintillators, materials that release photons when a particle hits them (see 6.5 Medical Imaging).



Rutherford expected that the particles would pass through the thin foil, as the alpha radiation has such high speed, however, he presumed that due to the wall of charge in their path they would on average be deflected to a large degree. However, the majority of the particles passed straight through with only a slight deflection of on average only a degree. This could not happen if, as in the Plum Pudding Model, the spheres of charge filled the space inside the foil uniformly. From this observation, Rutherford deduced that the atom is mostly empty space and so the mass must be concentrated at some point within the atom. Rutherford supposed that this must be the nucleus.

A small proportion of the alpha particles were deflected by more than 90°. This is only possible if the charge on the nucleus was the same as the charge on the alpha particle i.e. positive. Therefore, Rutherford concluded that the atom has a small dense nucleus which contains most of the mass of the atom and is positively charged. He also suggested the nucleus was surrounded by orbiting negative electrons which make the overall charge of the atom neutral. This model became known as the Rutherford or Planetary model of the atom.

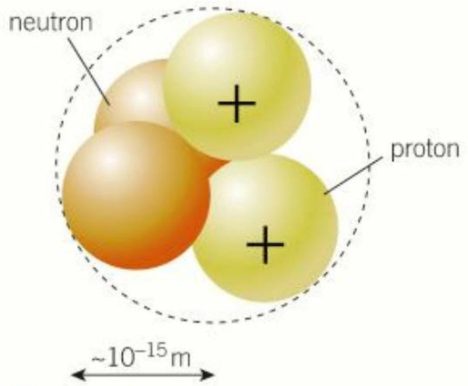




▲ **Figure 2** *Scattering of alpha particles by the positive gold nucleus*

Isotopes and Subatomic Particles

Isotopes are atoms of the same element with differing numbers of neutrons and so they can undergo the same chemical reactions but will undergo different nuclear reactions. This is due to their electronic configurations being identical however the stability of their nuclei may differ greatly.



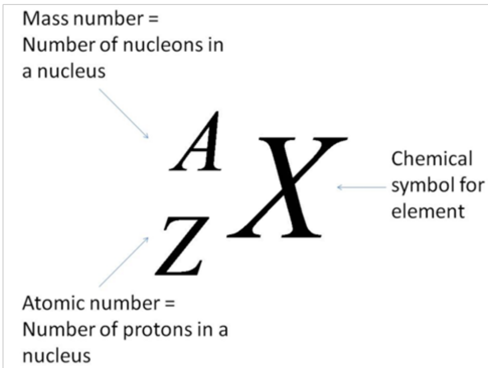
▲ **Figure 1** *A helium nucleus (alpha particle) with two protons and two neutrons*

N \ Z	1	2	3
6			$^{9}_{3}Li$
5			$^{8}_{3}Li$
4		$^{6}_{2}He$	$^{7}_{3}Li$
3		$^{5}_{2}He$	$^{6}_{3}Li$
2	$^{3}_{1}H$	$^{4}_{2}He$	$^{5}_{3}Li$
1	$^{2}_{1}H$	$^{3}_{2}He$	
0	$^{1}_{1}H$		

▲ **Figure 2** *Some isotopes shown by proton and neutron number on an N–Z grid*

A nucleon refers to a subatomic particle that resides in the nucleus of the atom and so is either a proton or a neutron. The proton has a charge that is equal and opposite to that of an electron i.e. $+e$ and so an atom must have an equal number of protons as electrons to remain neutral.

The subatomic particle constituents of an atom can be represented with the atomic or proton number, Z, and the mass number, A, (not to be confused with the relative atomic mass number which takes a weighted average of the mass numbers of the isotopes of an element, taking into account their relative abundance). The mass number, also known as the nucleon number, is simply a sum of the number of protons and neutrons in the nucleus.



An estimate for the mass of an atom can be gained by multiplying the mass number by the atomic mass unit ($1\text{u} = 1.661 \times 10^{-27}$kg) which is defined as one twelfth the mass of carbon-12. Yet this is only an estimate for an atom is often heavier than its constituent parts (see Mass-Energy Equivalence). Both protons and neutrons have a very similar mass which is close to one atomic mass unit.

Different isotopes of the same atom will then have differing numbers of nucleons and so differing mass numbers, hence our referral to C-12 to distinguish this isotope from the others found in nature (C-13 and C-14 (see Radiocarbon Dating)).

The gold nucleus has a radius of approximately 10^{-14} m which was estimated from the distribution of angles in Rutherford's alpha scattering experiment. The deflection is caused by the electrostatic repulsion between the gold nuclei and the alpha particles. As the charge ($+2e$) and energy of the alpha particles (~1.2×10^{-12}J) as well as the charge on the gold nuclei ($+79e$) were known Coulomb's law (see 6.2 Electric Fields) can be used to find the radius of the gold nucleus as it is related to the average distance between the charges. The radius of an atom is of order 10^{-10} m and so is 10,000 times greater than the radius of the nucleus.

The nuclear density is very high with a mass of order 10^{-25} (~100 nucleons of mass 1u) occupying a space of order 10^{-42} m^3 from the radius of the gold nucleus cubed. Therefore, as density is the mass per unit volume

$$\rho = \frac{m}{V} \approx \frac{10^{-25}}{10^{-42}} \approx 10^{17}\ \text{kgm}^{-3}$$

The radii of the nuclei were found to be directly dependent upon the relative atomic mass, A, of the nucleus. The radius of the nucleus, R, was found to follow the relationship

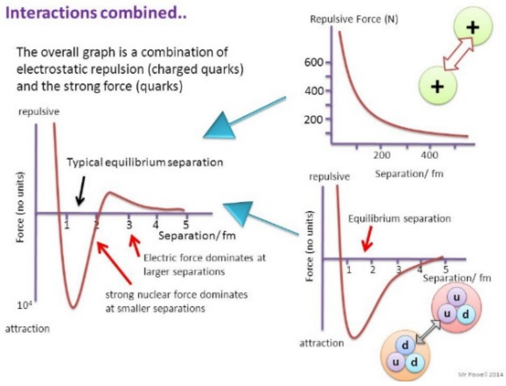
$$R = r_0 A^{1/3}$$

where r_0 is a constant equalling ~1.2 fm ($1\text{ fm} = 10^{-15}$m). This was constant determined via diffraction experiments in which electrons with known de Broglie wavelengths were directed at thin sheets of metal foil. The electrons have small enough de Broglie wavelengths and so from their diffraction patterns the size of the nuclei can be calculated.

Fundamental Forces

There are four fundamental forces in the universe:

- The gravitational force (comprising all weight and forces between bodies with mass such as stars galaxies and planets) acts on particles with mass. It is always attractive, has an infinite range but is very weak.
- The electromagnetic force (comprising of all electrostatic and magnetic forces as well as radiation pressure). It has an infinite range and acts on particles with charge.
- The weak nuclear force is the force responsible for beta decay. It acts to change quark types over very small distances.
- The strong nuclear force which acts between all nucleons and all quarks (i.e. the hadrons (see Fundamental Particles)) counteracts the repulsive electrostatic forces between protons in the nucleus and. It is attractive at small distances (up to ~3 fm) and repulsive at incredibly small distances (below ~0.5 fm) and has a limited range.



▼ **Table 1** *The four fundamental forces or interactions*

Fundamental force	Effect	Relative strength	Range
strong nuclear	experienced by nucleons	1	~10^{-15} m
electromagnetic	experienced by static and moving charged particles	10^{-3}	infinite
weak nuclear	responsible for beta-decay	10^{-6}	~10^{-18} m
gravitational	experienced by all particles with mass	10^{-40}	infinite

Mass-Energy Equivalence

Einstein hypothesized that energy and mass were linked by the mass-energy equivalence i.e. that mass and energy were different manifestations of the same thing or, to put it another way, mass can be thought of as energy in the form of mass-energy. Einstein's relation dictates that the energy change is proportional to the mass change and that the constant of proportionality is the speed of light squared i.e.

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

where ΔE is the change in energy, Δm is the change in mass and c is the speed of light in a vacuum.

The concept of mass as a form of energy is clearly demonstrated by the annihilation of matter and antimatter (see Antimatter), where the combined mass of the two particles is related by the mass-energy equivalence to the energy released in the annihilation event. Although, it could also be interpreted that energy has mass e.g. a faster moving object has more energy and so it has more mass. This change in mass is extremely small for low speeds as a factor of the inverse of the speed of light squared is the constant of proportionality (of the order ~10^{-17}). The concept of rest mass arises from this phenomenon. As any object, given high enough energy, can acquire an incredibly high mass, the only true measure of mass, the only mass agreed upon by all observers, is the mass of that object at rest.

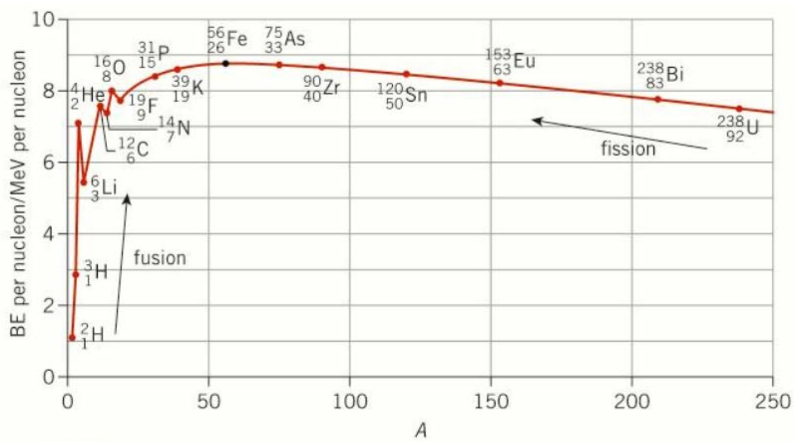
Mass Defect and Binding Energy

The energy, and therefore mass gained by an object, does not have to be in the form of kinetic energy though. The mass-energy equivalence applies to all forms of energy whether gravitational potential energy (the mass of an object should increase when lifted through a height), thermal energy (random kinetic energy of particles), electrostatic potential energy or the potential energy that arises from the strong nuclear force. The combination of the last two types of energy applied to nuclei is known as the binding energy.

This is why the mass of a helium atom is slightly lower than the mass of the constituent parts. The binding energy has increased and therefore the mass must decrease to obey mass-energy conservation. Binding energy, and in fact all forms of potential energy, are defined by the bound state having a more negative energy and the unbound state. Thus, if particles become more tightly bound their energy has decreased and so will their mass. A more formal definition of the binding energy is the minimum energy required to break a nucleus into its constituent components. Typically, the binding energy is quoted per nucleon to give a more comparable value for different nuclei.

In radioactive decays radiation is emitted either in the form of high energy particles or photons or both (see Radioactivity). This energy must come from a change in mass. When a parent nucleus emits a daughter nucleus and a high energy particle or photon, there is a mass difference between the total original mass and the total final mass of the products. This mass loss is known as the mass defect of the reaction. A formal definition of the mass defect as applied to nuclear synthesis can be stated as the difference in the mass of the constituent nucleons against the mass of the nucleus. This mass loss is due to the potential of the electrostatic and strong forces but can also be seen as a work required to separate constituent nucleons.

The figure below shows the binding energy per nucleon for different isotopes. The most stable isotope is iron-56 as it has the maximum binding energy per nucleon. For low nucleon numbers, $A < 56$, the binding energy per nucleon increases. This means that if two small nuclei such as ${}^2_1H$ and ${}^3_1H$ are combined there is a large decrease between the



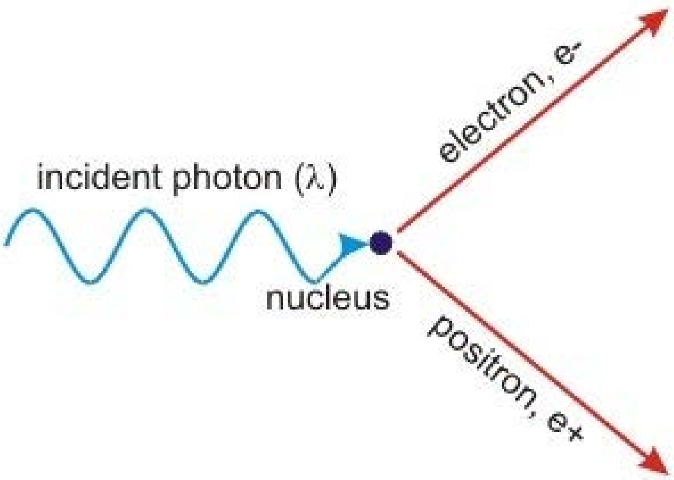
▲ **Figure 2** *Graph of binding energy per nucleon against nucleon number A for nuclei* mass of the two smaller nuclei and the resulting He nuclei. This is due to a significant increase in the strong attraction between nucleons compared to the small increase in the electrostatic repulsion. The mass defect causes energy to be released in this process which is known as fusion. Fusion is the process that generates the energy in stars (see Fusion).

For high nucleon numbers, $A > 56$, the binding energy per nucleon decreases. Therefore, breaking apart larger nuclei will release the binding energy and reduce the mass. This is due to the large proton number causing a large repulsive electrostatic force and a relatively feeble strong attraction due to an increased average distance between the nucleons. If a large nucleus is broken apart into two small and greater binding energy daughter nuclei then energy is released in a process known as fission (see Fission). Fission occurs in fission reactors which generate electrical energy for consumers globally.

Antimatter

Every particle has a corresponding antiparticle. The particle and antiparticle will have equal mass but opposite charge and so are attracted to each other. When these particles meet at a point in space, they annihilate to produce energy in the form of photons.

The process of pair production occurs when a high energy photon spontaneously creates a matter-anti matter pair (often an electron-positron pair, see 6.5 Medical Physics). To create this pair the photon must have an energy greater than the combined rest masses of the two particles and for this reason particle rest masses are often quoted in units of MeV/c^2. For example, using Einstein's relation and the rest mass of the positron and electron both being $\sim 0.51\ MeV/c^2$ (particle and antiparticles always have the same mass) it can be calculated that the minimum energy required to create these particles is 1.02MeV.



Fundamental Particles

Fundamental particles consist of two main classes: hadrons and leptons. Hadrons are made up of fundamental particles called quarks and are acted on by both the strong and the weak nuclear force. Quarks can only exist in quark-antiquark pairs, which make a class of hadrons called the mesons, or in groups of three with make up the baryons. Protons and neutrons are baryons whereas particles such as the pions are mesons. All baryons have a baryon number of 1. Antibaryons have a baryon number of -1.

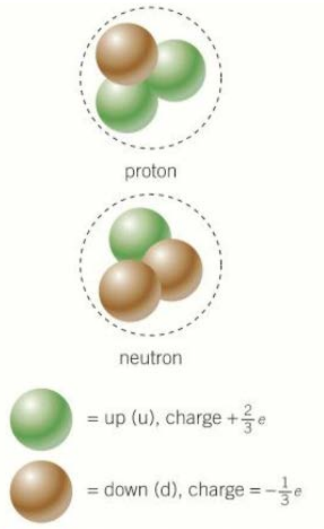
Quarks have fractions (either $\pm\frac{1}{3}$ or $\pm\frac{2}{3}$) of the elementary charge however they cannot be isolated i.e. they exist as mesons or baryons and so only whole numbers of the elementary charge have so far been found.

For example, protons are made up of three quarks, two up quarks and one down quark to create a particle of charge $+1e$. A neutron is made up of two down quarks and an up quark and so has a neutral charge. An antiproton is made up of the respective anti-quarks and so has a charge of $-1e$.

If quarks have never been detected in isolation, how do we know they exist at all? Well, their existence has been deduced from particle collisions. During a particle collision, some of the kinetic energy and mass-energy of the particles can be transferred into other forms and particles created or destroyed by the mass-energy equivalence. Conservation rules apply to these collisions such as conservation of mass-energy, conservation of momentum, conservation of charge and conservation of baryon and lepton number. Thus, particles with high energy cannot be created from lower energy collisions and so over time as larger higher energy particle colliders have been built higher energy particles have been discovered and the different flavours or types quark have been inferred.

▼ **Table 1** *The quarks and their properties*

Quarks			Anti-quarks		
Name	Symbol	Charge Q/e	Name	Symbol	Charge Q/e
up	u	$+\frac{2}{3}$	anti-up	$\bar{u}$	$-\frac{2}{3}$
down	d	$-\frac{1}{3}$	anti-down	$\bar{d}$	$+\frac{1}{3}$
charm	c	$+\frac{2}{3}$	anti-charm	$\bar{c}$	$-\frac{2}{3}$
strange	s	$-\frac{1}{3}$	anti-strange	$\bar{s}$	$+\frac{1}{3}$
top	t	$+\frac{2}{3}$	anti-top	$\bar{t}$	$-\frac{2}{3}$
bottom	b	$-\frac{1}{3}$	anti-bottom	$\bar{b}$	$+\frac{1}{3}$



▲ **Figure 1** *The quark combinations of the proton and the neutron*

In strong interactions, another property that must be conserved is the strangeness (as well as top-ness, charm etc.). If a hadron contains a strange quark it will have a strangeness of -1 and if it has an anti-strange quark it has a strangeness of 1 (it was an unfortunate mistake labelling the anti-strange particle -1 strangeness (the same happened for top, charm and bottom quarks) but we're stuck with it now). This is conserved unless the hadron decays via the weak force (see Beta Decay and the Weak Nuclear Force).

Leptons are also fundamental particles but unlike quarks they are not affected by the strong force. They are subject to the weak nuclear force however and so are created in nuclear decays such as beta decay to conserve the charge and mass-energy of the interaction. Leptons have a lepton number of 1 whereas their antiparticles have a lepton number of -1. Examples of leptons include electrons, positrons (antielectrons), neutrinos and muons. The neutrino (and also antineutrino) has a mass very close to zero and no charge so they rarely interact with matter making them difficult to detect.

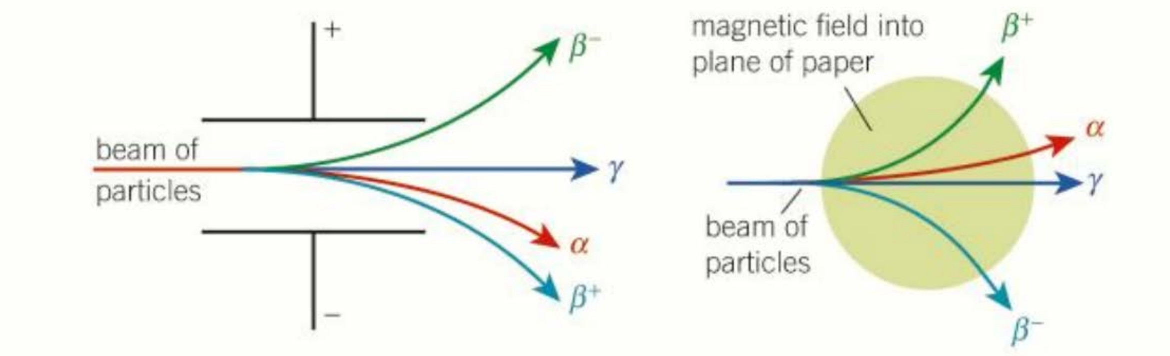
Radioactivity

Radioactive decay is the spontaneous breakdown of an atomic nucleus resulting in the release of energy and matter from the nucleus. It is a random process meaning that it is impossible to predict which of a number of identical nuclei will decay next. Yet each decay follows a defined pattern and given a large enough number of nuclei this yields predictable results. The half-life is the time taken on average half of the active isotopes in a radioactive sample to decay. This means although we cannot be sure which half will decay but we can be reasonably certain that approximately half the sample decay. Of course there is a minute probability that none of the sample decay but given a large enough sample this probability becomes improbably small. For example, if we had 10 nuclei the probability that none of them decay in the half-life of the sample is the same as throwing 10 heads in a row i.e. $\left(\frac{1}{2}\right)^{10} \approx 0.00098$ so approximately 0.01%. However, if we take just 1 mole of a sample of say C-14 that would weigh 14 grams and have 6.022×10^{23} nuclei, the probability that none of those nuclei decay in the half-life is then $\left(\frac{1}{2}\right)^{6.022\times10^{23}}$ which is vanishingly small.

Radiation comes in three main forms.

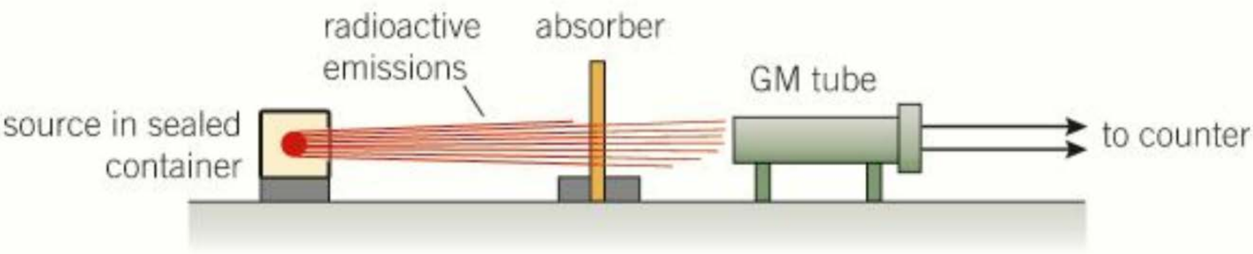
Radiation type	Alpha Particle	Beta Particle	Gamma Ray
Symbol	α or ${}^4_2\alpha$ or ${}^4_2He$	β or β^-	γ
Mass (u)	4	1/2000	0
Charge	+2	-1	0
Speed	Slow	Fast	Speed of Light
Ionising Ability	High	Medium	None
Penetrating Power	Low	Medium	High
Stopped by	Paper	Aluminium	Lead

These different types of radiation can be easily distinguished as they each have different penetrating powers so simply screening the source with different materials and measuring the drop in activity should allow for the type of source to be determined. In addition to this, all three have different responses to magnetic fields and electric fields due to their differing charges making specific radiation detectors easy to design.



▲ **Figure 2** *The effect of a uniform electric field and a uniform magnetic field on the paths of different types of radiation*

Examples of radiation detectors include bubble chambers (see 6.3 Electromagnetism) which use tanks of water that from tracks of bubbes when ionising particles pass through them and Geiger-Muller tubes (Geiger counters) which form cascades of electrons when an ionising particle hits the detector.



▲ **Figure 3** *Experimenting with radiation and different absorbers*

Beta Decay and the Weak Nuclear Force

The weak nuclear force causes the transformation of quarks via emission of leptons. In beta minus decay, the weak force mutates a down quark into an up quark within a neutron transforming it into a proton. This process releases energy in the form of a high speed electron or beta particle which is also needed to conserve charge. However, an antineutrino is also created in order to conserve lepton number.

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\bar{v}_e$$

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{v}_e$$

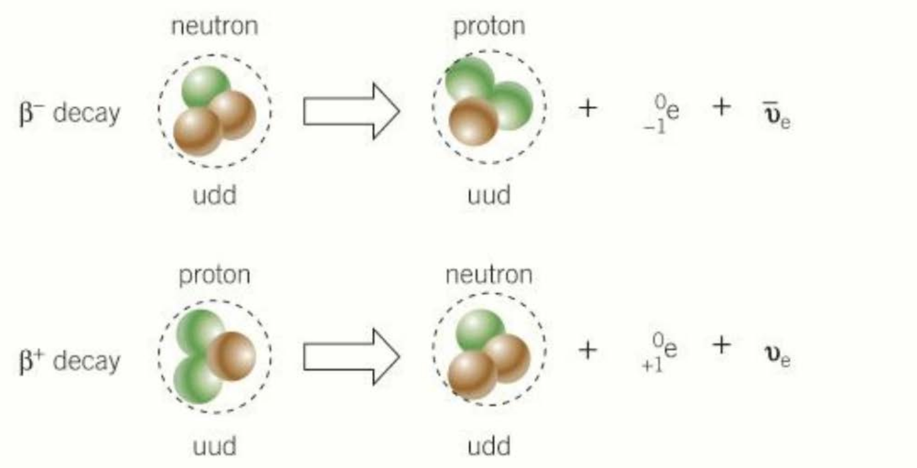
$$d \rightarrow u + {}^{0}_{-1}e + {}^{0}_{0}\bar{v}_e$$

Beta plus decay also occurs when an up quark transforms into a down quark in a proton changing it to a neutron. Again, energy is produced creating a positron and neutrino.

$$^{A}_{Z}X \rightarrow {}_{Z-1}^{\;\;A}Y + {}^{\;\;0}_{+1}e + {}^{0}_{0}\nu_e$$

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e + \nu_e$$

$$u \rightarrow d + {}^{0}_{1}e + \nu_e$$



▲ **Figure 2** *Quark transformations in beta decays*

In this decay charge again is conserved. On the left-hand side, the proton has a +1 charge, the neutron and neutrino have no charge but the positron has a +1 charge. The lepton number of the positron is -1 so a neutrino is also created to conserve the lepton number.

Radioactive Decay Equations

Alpha decay occurs in very unstable nuclei and sees the loss of an alpha particle or helium nucleus. Alpha emission can be thought of as spontaneous fission of unstable nuclei in which the strong nuclear force is not great enough to overcome the electrostatic repulsion between protons in the nucleus. The high binding energy per nucleon of the helium nucleus makes this daughter nucleus a favourable choice as total binding energy will increase vastly as the parent nuclei moves closer to the middle of the binding energy per nucleon graph. There is a large energy loss from the unstable nuclei because of this though no quarks change type or flavour.

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

A common occurrence in nuclear decays is many will happen in succession until a stable atom is reached, this process of decaying is called a decay chain and shows the changing proton and neutron numbers and the type of decay undergone to go between each step.

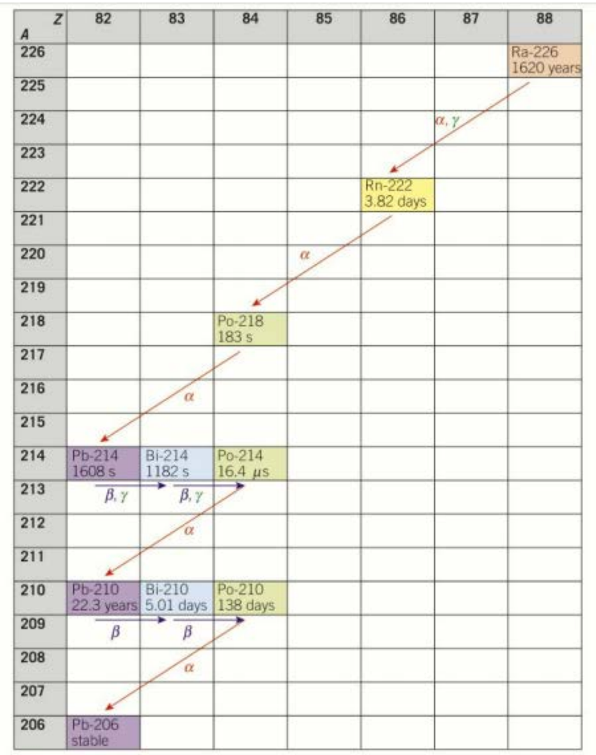
As the proton number of a nucleus rises the electromagnetic repulsive force between the nucleons rises. For these nuclei to not fall apart there must be more nucleons to produce a strong force attraction. Therefore, for large values of proton number the most stable nuclei have more neutrons than protons. If we plot the neutron number versus the proton number of isotopes we can identify a belt of stability.

Nuclei with greater than 82 protons are more likely to decay via alpha radiation.

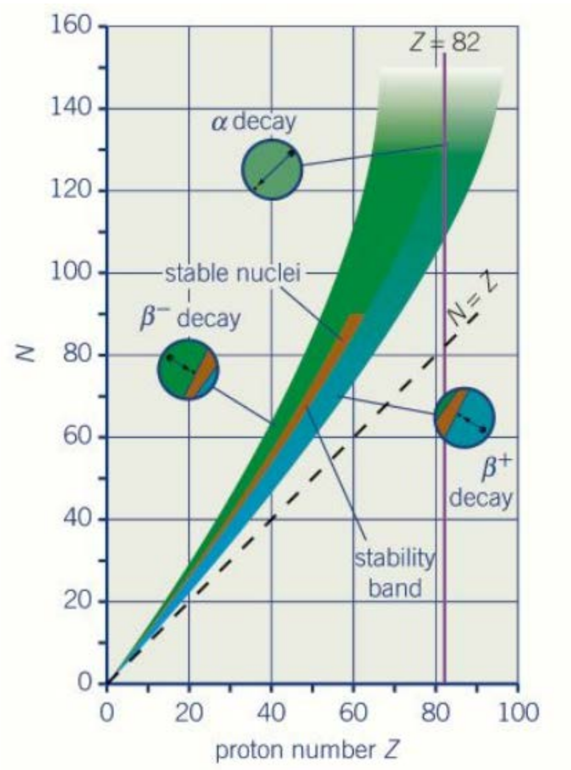
Nuclei to the right of the belt of stability have too many protons and therefore are proton-rich meaning that they are more likely to decay via beta-plus decay.

Nuclei to the left of the belt of stability have too many neutrons and therefore are neutron-rich meaning that they are more likely to decay via beta-minus decay.

Gamma decay is caused when a nucleus has surplus energy following alpha or beta emission. There is no change to nucleon composition, but energy is released in the form of a gamma photon.



▲ **Figure 2** *The decay chain for radium-226 – a sample initially made of pure radium-226 can end up as 10 different isotopes*



▲ **Figure 3** *N–Z plot of nuclei*

Activity

The activity of a source is the rate at which nuclei decay, or number of decays per second, measured in Becquerel (s^{-1}). This activity depends on the half-life and the number of active nuclei in the sample, N.

For a very large sample we can assume that the number of unstable nuclei in a sample will change at a rate proportional to the total number of unstable nuclei:

$$\Delta N \propto N\Delta t$$

yet activity is defined as the rate of change of the number of unstable nuclei, N, so

$$A \propto N$$

This proportionality can be given a constant

$$A = \lambda N$$

known as the decay constant, λ (s^{-1}). This is the probability that an individual nucleus will decay per unit time.

Often the recorded activity during an experiment will be far higher than that of the sample under consideration alone. This is due to the experiment also measuring the background radiation (radiation due to cosmic rays, naturally occurring radioactive compounds and anthropogenic sources e.g. nuclear power plants) which increase the measured activity. To allow for this false reading, the background must first be measured without the sample nearby and then the background must be deducted from the activity measured in the presence of the sample.

Exponential Decay

In the limit of infinitesimal time steps the above equation can be taken as

$$\frac{dN}{dt} = -\lambda N$$

By separating variables and integrating, this differential equation can be solved and using the initial condition that at the start there is a known number of unstable nuclei N_0 *so that* $N(t = 0) = N_0$.

$$N = N_0 e^{-\lambda t}$$

hence as $A = \lambda N$

$$A = \lambda N_0 e^{-\lambda t} = A_0 e^{-\lambda t}$$

Another way of demonstrating this decay is to iteratively calculate N from the equation $\frac{\Delta N}{\Delta t} = -\lambda N$ for some small time interval Δt which must be small in comparison to the half-life. This will also give the exponential relationship (see 6.2 Capacitors).

The half-life, $t_{1/2}$, of a decay is the average time it takes for half of the sample to decay, so substituting $N = \frac{N_0}{2}$ into the above we find that $\lambda t_{1/2} = \ln(2)$. Thus, if the decay constant is known the half-life can be found.

The activity is the quantity detected in experiment using a Geiger-Muller tube but if a mass spectrometer is used to find the abundance of the active isotope in the sample and the sample is weighed, the number of active isotopes can be found and then the decay constant deduced from the relation $A = \lambda N$.

Alternatively, the half-life can be calculated directly from the activity by recording activity versus time and using a logarithmic scale. The graph should give a straight line which represents $\ln(A) = \ln(A_0) - \lambda t$. The gradient will be the negative of the decay constant. On a regular plot of activity versus time, the time taken for the activity to half will give an estimation of the half-life although this is only practical if the half-life is on the order of days, hours or minutes.

Radiocarbon Dating

Naturally occurring carbon in the atmosphere contains three main isotopes, C-12, C-13 and C-14. The ratio between these isotopes is a known constant, approximately 99% is C-12, 1% C-13 and C-14 exists in trace amounts (around 1 atom per gram of carbon). Living organisms absorbs C-14 during their lifetimes either through photosynthesis of CO_2 or through the consumption of other organisms containing carbon. Therefore, the ratio of C-14 to C-12 in the organism will match the atmospheric ratio yet at the point of death the number of C-14 atoms will be capped. C-14 is a radioactive isotope that decays via beta emission with a half-life of ~5700 years. Hence, by measuring the ratio of C-14 to C-12 in the dead tissue and comparing this to the atmospheric composition an estimation for the time since the organism's death can be calculated.

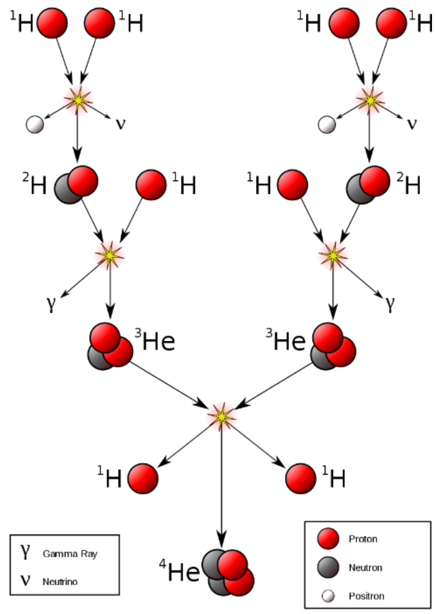
Radiocarbon dating is not a perfect technique however, firstly it assumes the ratio of C-12 to C-14 has remained constant throughout history. Also, for small samples the amount of C-14 in the sample can be unnoticeable in comparison to the background radiation. Finally for samples much older than 5700 years, the amount of C-14 becomes immeasurably small so this technique cannot be used. Instead, rubidium is often used due to its longer half-life.

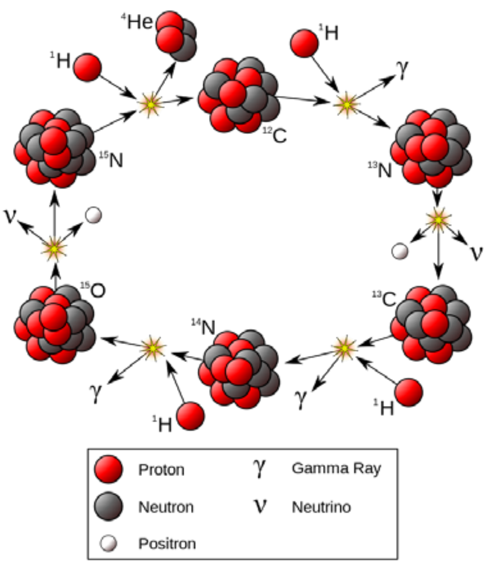
Nuclear Fusion

In stars, small nuclei are fused together to produce larger nuclei and energy. In order to fuse two nuclei together the particles must first overcome the electrostatic repulsion between them. This requires high temperatures and pressures which occur due to the gravitational pressure generated by the outer layers of the star pressing inwards on the star's core under gravity.

In main sequence stars such as the sun, stellar fusion occurs via the proton-proton chain in which lone protons in the star's plasma fuse to form an unstable ^2_2He nuclei. This particle then undergoes beta decay forming deuterium nuclei (^2_1H, an isotope of hydrogen). The next reaction in the chain fuses deuterium with a further proton to form ^3_2He and so the process continues forming nuclei up to ^4_2He.

In larger stars, fusion occurs predominantly via the CNO cycle in which carbon, nitrogen and oxygen are synthesised. The heaviest elements are synthesized by fusion that occurs as a more massive star undergoes a violent supernova at the end of its life in a process known as supernova nucleosynthesis.





Artificial fusion reactors are currently being developed as alternative power sources as they have no radioactive by-products. However, the extremely high temperatures and pressures needed to maintain fusion and can only be operated for short periods of time (see 6.3 Electromagnetism).

<u>Nuclear Fission</u>

Fission is the breaking apart of large nuclei into small nuclei causing a reduction in the total binding energy, a mass defect and energy to be released. Typically, uranium-235 is used the fissile material as it easily undergoes fission and is relatively abundant. A low speed, thermal neutron is fired at the U-235 nuclei which absorbs the extra nucleon to become the unstable U-236 isotope. This isotope then either decays via fission (about 85% of the time), splitting into two smaller daughter nuclei and more fast neutrons or decays via gamma emission.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow [{}^{236}_{92}U] \xrightarrow{85\%} fission\ (e.g.\ {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\ {}^{1}_{0}n) $$

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow [{}^{236}_{92}U] \xrightarrow{15\%} {}^{236}_{92}U + \gamma $$

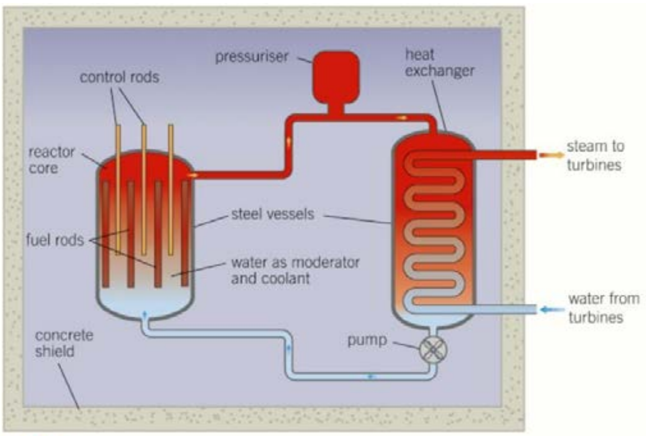
In fission, the mass of the daughter nuclei is always less than the mass before, excess mass is transformed into energy. The total energy released is the combination of the kinetic energy of the neutrons and daughter nuclei and the energy of the photons.

Fission Reactors

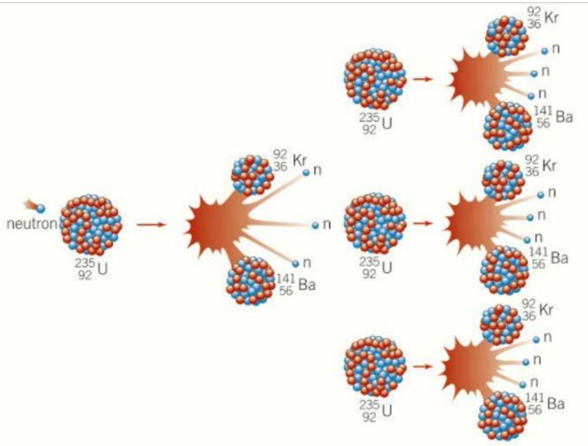
All fission reactors have similar key components. The fissile materials sit inside a reactor core which is surrounded by a thermal coolant which absorbs the thermal energy from the fission and transforms this thermal energy into kinetic energy in the turbines which then turn the generator transferring this energy into electrical energy i.e. alternating current (see 6.3 Electromagnetism). The fuel rods within the core contain the fissile material and are surrounded by the moderator and control rods.

The absorption of neutrons and consequent fission is more likely to occur with slower neutrons, which means the neutrons released by the fission process are too high energy to continue the reaction. They are slowed by a moderator (e.g. water, graphite) which increases the chance a chain of U-235 fission reactions. The rate of the reaction is controlled by control rods (e.g. boron, cadmium) which absorb thermal neutrons to prevent these neutrons from causing further fission reactions. This is used to reduce the rate of the reaction if it is deemed too high e.g. if the reactor core is overheating.

The products of fission reactions are also typically also radioactive and known colloquially as toxic waste. One example is Plutonium-239 which has a half-life of ~24,000 years and so remains hazardous for millenia. It cannot be simply disposed off and so must be contained in a way that is future proof. The waste is often buried deep underground so it cannot be accessed. These burial locations must be safe from attack and designed to be protected against earthquakes.



▲ **Figure 4** *The main components of a water-cooled reactor*



▲ **Figure 3** *An uncontrolled chain fission reaction*