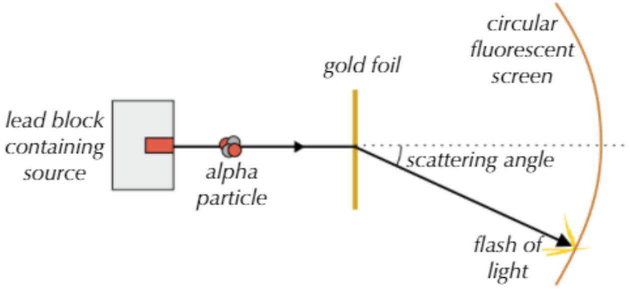
Module 6 Section 4: Nuclear and Particle Physics

Atomic Structure: Rutherford alpha particle scattering experiment



- Most of the alpha particles went straight through the foil. So the atom is mainly empty space.
- Some of the alpha particles were deflected through large angles, so the centre of the atom must have a highly positive charge to repel them. Rutherford named this the nucleus.
- Very few particles were deflected by angles greater than 90°, so the nucleus must be tiny.
- Most of the mass must be in the nucleus, since the fast alpha particles (with high momentum) were deflected backwards by the nucleus.

Nuclear Model of the Atom

Particle	*Charge (C)*	*Mass (kg)*
Proton	$+1.60 \times 10^{-19}$	1.673×10^{-27}
Neutron	0	1.675×10^{-27}
Electron	-1.60×10^{-19}	9.11×10^{-31}

The Nucleus

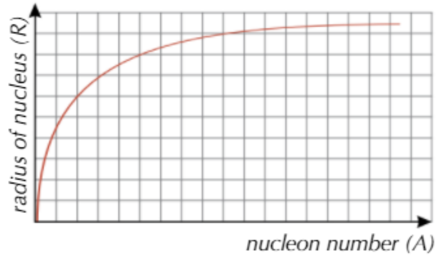


Figure 1: *A graph of nuclear radius, R, against nucleon number, A.*

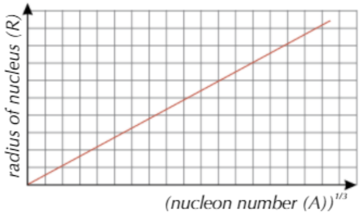


Figure 2: *A graph of nuclear radius, R, against the cube root of nucleon number, A.*

R *= nuclear radius* → $R = r_0 A^{1/3}$ ← ***A*** *= nucleon number*

Particles and Antiparticles

Not all particles can feel the strong nuclear force — the ones that can are called **hadrons**. Hadrons also feel the weak nuclear force. Hadrons aren't **fundamental particles**. They're made up of smaller particles called quarks

Most hadrons will eventually decay into other particles.
The exception is protons — most physicists think that protons don't decay.

The neutron is an unstable particle that decays into a proton (along with an electron and an antineutrino). The decay of a neutron is really just an example of β⁻ decay (see p.427), which is caused by the **weak nuclear force**.

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

neutron → n; *proton* → p; *electron* → e^-; *antineutrino (see page 420)* → $\bar{\nu}$

Free neutrons (i.e. ones not in a nucleus) have a half-life of about 15 minutes. (The neutron is much more stable when it is part of a nucleus.)

Particle/Antiparticle	**Symbol**	**Relative Charge**	**Rest Mass (kg)**
proton	p	+1	1.673×10^{-27}
antiproton	$\bar{p}$	–1	
neutron	n	0	1.675×10^{-27}
antineutron	$\bar{n}$		
electron	e^-	–1	9.11×10^{-31}
positron	e^+	+1	
neutrino	ν	0	0
antineutrino	$\bar{\nu}$		

Leptons are fundamental particles and they don't feel the strong nuclear force. They interact with other particles via the weak nuclear force and gravity (and the electrostatic force if they're charged).

Name	**Symbol**	**Relative charge**
electron	e^-	–1
neutrino	ν	0

When energy is converted into mass you get equal amounts of matter and antimatter. So if an extra proton is formed then there will always be an antiproton to go with it. It's called **pair production**.

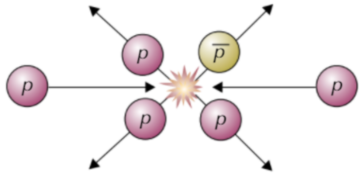


Figure 4: *Pair production — two protons colliding and producing a proton-antiproton pair.*

When a particle meets its antiparticle the result is **annihilation**.
All the mass of the particle and antiparticle gets converted to energy, in the form of a pair of photons. Antiparticles can usually only exist for a fraction of a second before this happens, so you don't get them in ordinary matter.

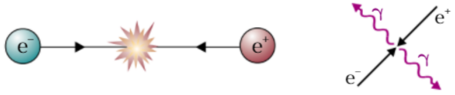


Figure 7: *Electron-positron annihilation.*

Module 6 Section 4: Nuclear and Particle Physics

Quarks and Antiquarks

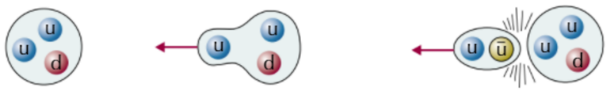
Name	Symbol	Charge
up	*u*	*+2/3 e*
down	*d*	*–1/3 e*
strange	*s*	*–1/3 e*

Name	Symbol	Charge
anti-up	$\bar{u}$	*–2/3 e*
anti-down	$\bar{d}$	*+1/3 e*
anti-strange	$\bar{s}$	*+1/3 e*

Protons are made of two up quarks and one down quark (uud).
- The total charge of a proton is 2/3 + 2/3 + (– 1/3) = +1.

Neutrons are made up of one up quark and two down quarks (udd).
- The total charge of a neutron is 2/3 + (–1/3) + (–1/3) = 0.

Figure 2: *The quark composition of nucleons.*



A proton.

Energy supplied to remove u quark.

When enough energy is supplied, a u and ū pair is produced and the u quark stays in the proton.

Figure 3: *Quark confinement — the energy used trying to remove a u quark only creates a u and ū pair in a pair production.*

Binding Energy

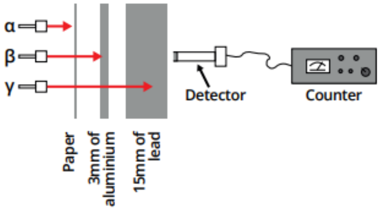
Binding energy is the energy that has to be supplied in order to dissociate a nucleus into its constituent nucleons.

This is the energy released when the nucleons form a nucleus. Separately, having so many charged particles so close together is very unstable and therefore they have a high potential energy, forming a nucleus makes it more stable and the nucleons lose some potential energy. This is released and is equivalent to the mass lost.

Nuclear Decay

Radiation	Symbol	Constituent	Relative Charge	Mass (u)
Alpha	α	A helium nucleus — 2 protons & 2 neutrons	+2	4
Beta-minus (Beta)	β^- or β	Electron	–1	(negligible)
Beta-plus	β^+	Positron	+1	(negligible)
Gamma	γ	Short-wavelength, high-frequency electromagnetic wave.	0	0

Radiation	Symbol	Ionising Power	Speed	Penetrating power	Affected by magnetic field
Alpha	α	Strong	Slow	Absorbed by paper or a few cm of air	Yes
Beta-minus (Beta)	β^- or β	Weak	Fast	Absorbed by ~3 mm of aluminium	Yes
Beta-plus	β^+	Annihilated by electron — so virtually zero range			
Gamma	γ	Very weak	Speed of light	Absorbed by many cm of lead, or several m of concrete	No



Differentiating between sources of radioactivity can be done by studying their penetrating properties. The more ionising the radiation, the less penetrating it is.

Remember to correct for background radiation in any data used. This involves subtracting the value of the background, either given or calculated from the data with no source present, from the value measured.

Half Life

Half-life, $T_{½}$, is defined as the time taken for the **number of radioactive nuclei**, N (or the activity A) to **reduce to one half** of the initial value. It does not change for a radioactive sample. After one half-life the activity will halve; after another half-life it will halve again to ¼ of its original value.

The number of nuclei remaining (or activity) can be calculated by this equation:

$$N = \frac{N_o}{2^x} \text{ or in terms of activity } A = \frac{A_o}{2^x}$$

where x is the number of half-lives.

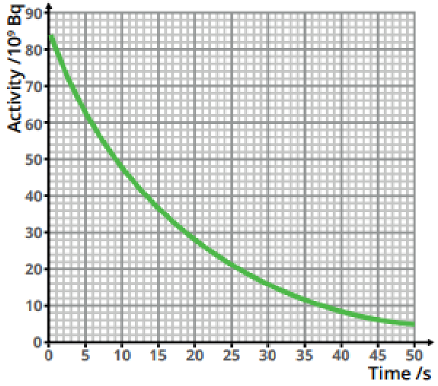
As the rate of decay (A) will be proportional to the number of nuclei (N), it is possible to express this in an equation:

$$A = \lambda N$$

where λ is the decay constant.

Exponential Law of Decay

Nuclear decay produces an exponential graph.



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

N *= the number of undecayed nuclei remaining*

N_0 *= the original number of undecayed nuclei*

t *= time in s*

λ *= the decay constant in* s^{-1}

Module 6 Section 4: Nuclear and Particle Physics

Fission and Fusion

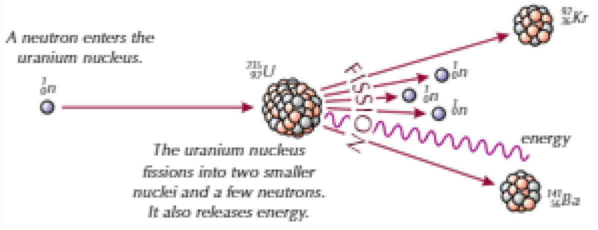
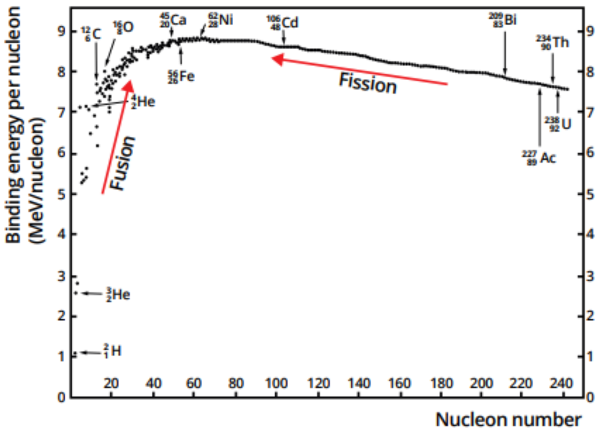


Figure 1: A possible fission of a uranium-235 nucleus.

Figure 2: Two isotopes of hydrogen fuse to form helium.



When nuclei undergo **fission or fusion** reactions, they form more stable nuclei with a **higher binding energy per nucleon**, the extra energy is released as kinetic energy or as photons.

Fission Reactors

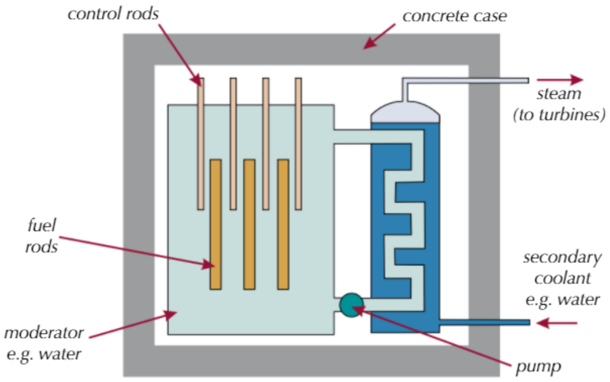


Figure 1: The key features of a thermal fission reactor.

Chain reactions

Fission reactors use rods of uranium that are rich in ^{235}U (or sometimes plutonium rods rich in ^{239}Pu) as 'fuel' for fission reactions. (The rods also contain other isotopes, but they don't undergo fission.)

These fission reactions produce neutrons which then induce other nuclei to fission, which produce more neutrons which go on to induce more fission. This is called a **chain reaction**. The neutrons will only cause a chain reaction if they are slowed down, which allows them to be absorbed by the uranium nuclei — these slowed down neutrons are called thermal neutrons (see page 445).

If the chain reaction in a fission reactor is left to continue unchecked, large amounts of energy are released in a very short time. Many new fission reactions will follow each fission, causing a runaway reaction which could lead to an explosion. This is what happens in a nuclear fission bomb.

Moderator

Fuel rods need to be placed in a **moderator** (for example, water) to slow down and/or absorb neutrons. You need to choose a moderator that will slow down some neutrons enough so they can cause further fission, keeping the reaction going at a steady rate.

Control rods

You want the chain reaction to continue on its own at a steady rate, where one fission follows another. The amount of 'fuel' you need to do this is called the **critical mass** — any less than the critical mass (sub-critical mass) and the reaction will just peter out. Fission reactors use a supercritical mass of fuel (i.e. more than the critical mass, so that several new fissions normally follow each fission) and control the rate of fission using **control rods**.

Control rods control the chain reaction by limiting the number of neutrons in the reactor. They absorb neutrons so that the rate of fission is controlled. Control rods are made up of a material that absorbs neutrons (e.g. boron), and they can be inserted by varying amounts to control the reaction rate. In an emergency, the reactor will be shut down automatically by the release of the control rods into the reactor, which will stop the reaction as quickly as possible.

Coolant

A coolant is a substance which transfers heat in a reactor. The material used should be a liquid or gas at room temperature, so that it can be pumped around the reactor, and be efficient at transferring heat. The moderator can serve as a primary coolant, which transfers the heat produced by fission to another coolant (the secondary coolant), such as water, which is converted to steam as it's heated. This steam then passes through and powers electricity-generating turbines.

Figure 3: Cooling towers at a nuclear power plant. The steam used to drive the turbines is passed through the cooling tower to cool it down.