

Module 6

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6.1 - Capacitors

Core Info and Definitions

A capacitor is a circuit component that stores charge in a circuit by separating equal and opposite charges onto two electrical conductors (plates) with an insulator in between them.

Capacitance, C , defines the quantity of charge Q which can be stored per unit potential difference across the plates. Measured in farads

Capacitance

$$C = QV = \frac{\epsilon_0 \epsilon_r A}{d}$$

... where epsilon 0 is the permittivity of free space, epsilon r is relative permittivity of the material, A is the surface area of a plate, and d is the separation between the plates.

Capacitance of an Isolated Conducting Sphere:

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

$$V = \frac{Q}{4\pi\epsilon_0 R}$$

Thus,

$$C = Q \times \frac{4\pi\epsilon_0 R}{Q}$$

$$C = 4\pi\epsilon_0 R$$

... where R is the radius of the sphere.

Total Circuit Capacitance

In series, capacitance sum is determined in a similar way to how resistance is determined with resistors in parallel:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_n}$$

In parallel, it's the opposite - the capacitances are just added to each other:

$$C = C_1 + C_2 + C_3 + \cdots + C_n$$

Capacitor Energy

Capacitor energy can be given as:

$$\begin{aligned} W &= \int_0^Q V \, dQ \\ &= \int_0^Q \frac{Q}{C} \, dQ \\ &= \frac{Q^2}{2C} \\ &= \underline{\underline{\frac{1}{2}QV}} \end{aligned}$$

... and you can use $Q=CV$ to substitute values in to determine energy with charge.

(You do not need to know the integral derivation. It is only for explanation.)

The work done in moving a charge Q from one plate to another through a **constant potential difference** V is:

$$\begin{aligned} \Delta W &= \int_0^{\Delta Q} V \, dQ \\ &= \underline{\underline{\Delta QV}} \end{aligned}$$

The reason the two energy equations are different is because **V is constant in the latter**, but **not the former**. Capacitance is a constant for each capacitor, however.

A capacitor can leak charge . This is because the insulator between the plates is not perfect, so there is a tiny current that passes through them. This charge leakage is more clearly observable when disconnecting a capacitor from the source of emf.

Charging and Discharging

Where x_0 is the initial value of the variable, C is capacitance, R is resistance and t is elapsed time:

	Current	Charge	PD
--	---------	--------	----

Charging	$I = I_0 e^{\frac{-t}{CR}}$	$Q = Q_0(1 - e^{\frac{-t}{CR}})$	$V = V_0(1 - e^{\frac{-t}{CR}})$
Discharging	$I = I_0 e^{\frac{-t}{CR}}$	$Q = Q_0 e^{\frac{-t}{CR}}$	$V = V_0 e^{\frac{-t}{CR}}$

(... yes, current has the same equation for charging and discharging.)

The time taken for the charge of the capacitor to fall to $1/e$ ($\sim 37\%$) of its original charge is known as the time constant.

$$\tau = CR$$

As more charge is added to a capacitor, it gets harder to add more charge to it. This concept is analogous to pumping a car tyre - it is initially easy to add air to it, but the increase of internal pressure makes adding more harder and harder.

Graphical Methods

Take V in discharging for an example. You can apply the natural logarithm " $\ln$ " to both sides to separate variables and obtain a straight line in a graph:

$$V = V_0 e^{\frac{-t}{CR}} \rightarrow \ln(V) = \ln(V_0) + \frac{-t}{CR}$$

In here, the y-intercept is " $\ln(V_0)$ " and the gradient is " $-1/CR$ ". You can use the gradient to find the capacitance of the circuit, and you can use the y-intercept to find the initial pd of the capacitor by raising e to the power of " $\ln(V_0)$ ".

Spreadsheet Modelling

You can model the discharge of a capacitor using a spreadsheet method without using experimental data. This is known as iterative modelling. You can do this with the following equation:

$$\Delta Q = \frac{Q}{CR} \times \Delta t$$

This gives the decrease of charge, so the output of this should be subtracted from the last value of charge. The table looks like this¹:

t/s	$\Delta Q / \mu C$	Q / μC
0.0	20	1000
0.1	19.6	980.0
0.2	19.2	960.4
0.3	18.8	941.2
0.4	18.4	922.4

... with a time increment of +0.1.

6.2 - Electric Fields

Definitions and Core Info

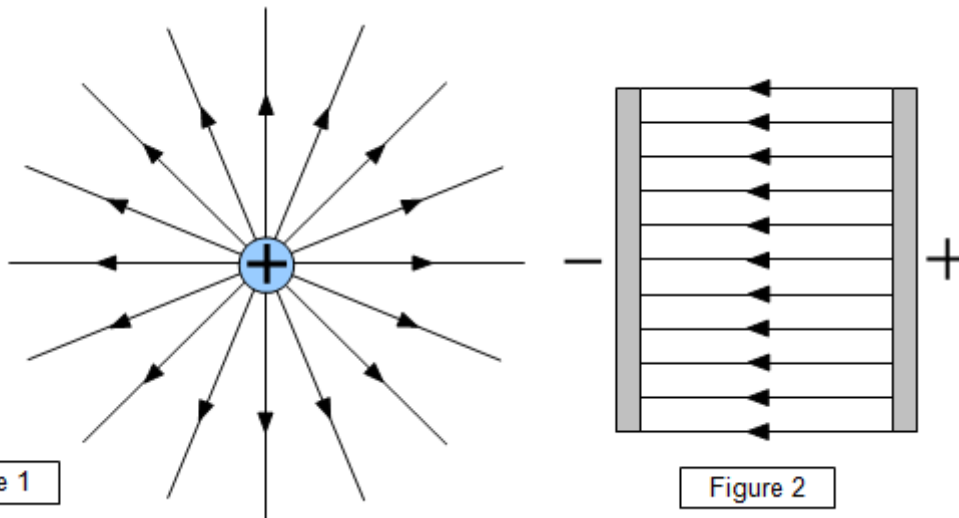
An electric field is a region around a body in which other charged bodies will feel a force. The direction of the field is the direction of the force experienced by a positive test charge.

$$E = \frac{F}{Q} = \frac{Q}{4\pi\epsilon_0 r^2}$$

... where F is the size of the electrical force, Q is the size of the charge, epsilon 0 is the permittivity of free space, and r is the distance between the charged point and any point in the field.

Electric Field Lines

Radial field vs uniform field¹:



The spacing between field lines represents the strength of the field.

The field between different types of charged surface¹:

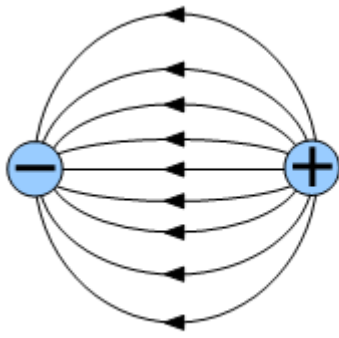


Figure 3

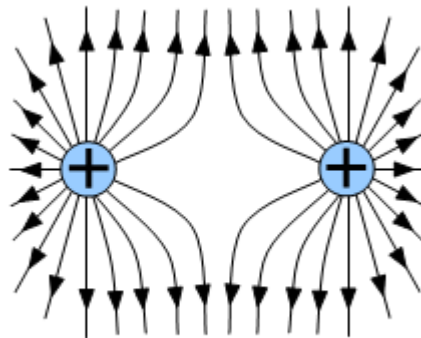


Figure 4

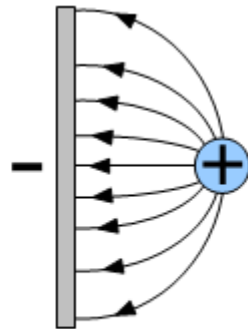


Figure 5

The neutral point is between two like-charged particles, showing where no electric force is experienced.

Coulomb's Law

$$F = \frac{Qq}{4\pi\epsilon_0 r^2}$$

... where Q and q are the charges of two charged points, epsilon 0 is the permittivity of free space, and r is the shortest distance between these charged points.

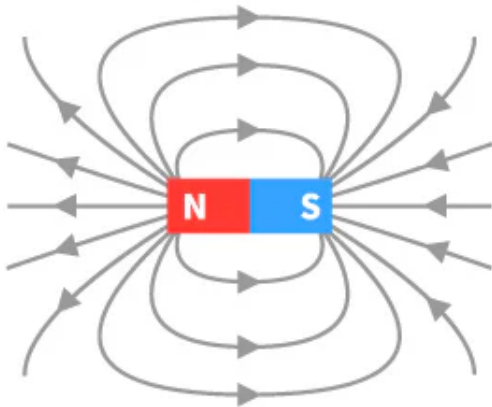
6.3 - Electromagnetism

Definitions and Core Info

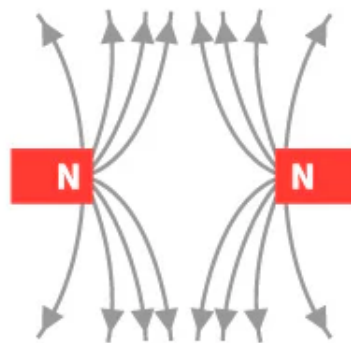
A magnetic field is a field in which a charged particle experiences a force. Its direction is determined by the force experienced by a positive test charge.

Field Lines

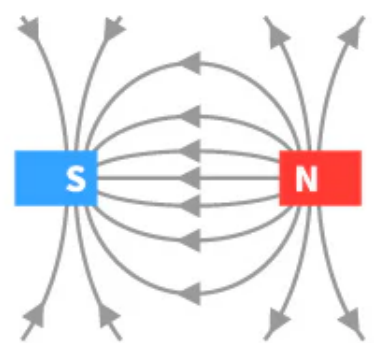
Bar magnet



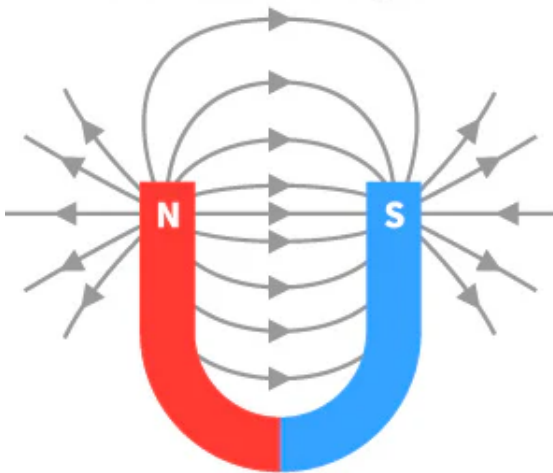
Like poles repel



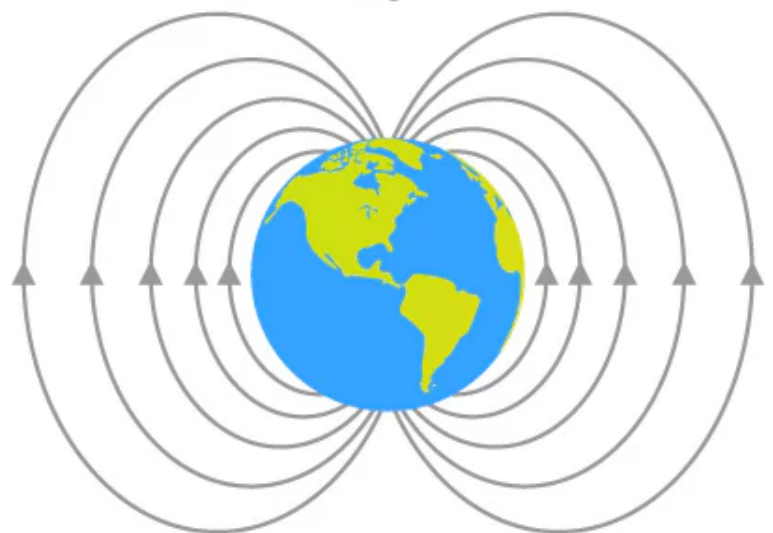
Unlike poles attract



Horseshoe magnet



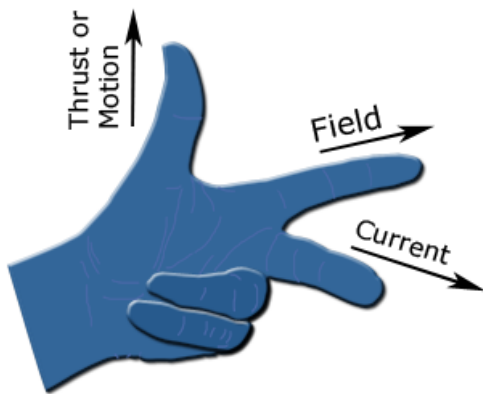
Earth's magnetic field



Magnetic Force

Flemings' left hand rule:

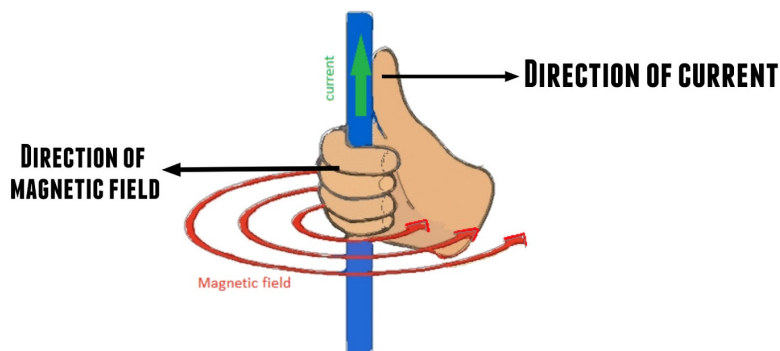
- **Thumb:** Thrust (force)
- Index/**F**irst finger: Magnetic field
- Middle/**S**econd: Current



This rule is executed on the right hand (Flemings' right hand rule) if the wire is moving through a uniform magnetic field to determine the force on the wire. Not really necessary once you understand Lenz's law.

Right hand grip rule:

- Thumb: Direction of magnetic field.
- Grip: Direction of current in the coil.



The "thrust" represents the magnetic force on a current-carrying wire/moving charge:

$$F = BIL\sin(\theta) \quad , \quad F = BQv$$

... where theta is the angle between the wire and the field lines.

In a magnetic field, a moving charge moves in circular motion. The radius is derived as:

$$F = BQv$$

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

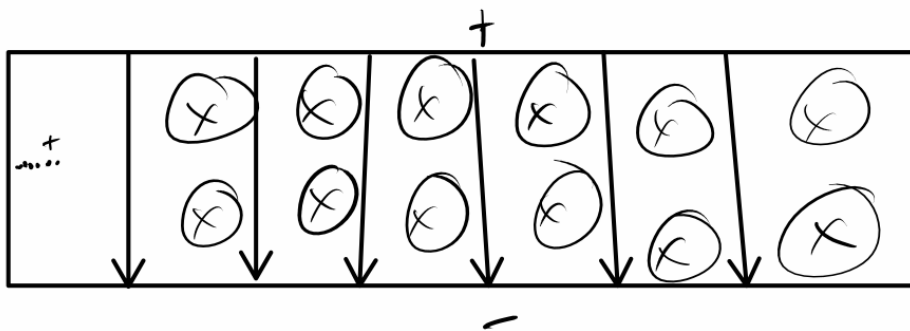
$$r = \frac{mv^2}{BQv}$$

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

... where m is the mass of the particle, v is its velocity, B is the magnetic flux density it is going through, and q is its charge.

This can be used to perform selection of certain particles by their velocity.

1. Particles are charged such that they all have the same charge.
2. They are accelerated through an electric field on top of a magnetic field through a vacuum.
3. $F = BQv$, $F = Eq$, $\Rightarrow E = Bv$
4. Particles with the incorrect velocity will have unbalanced forces, causing them to undergo circular motion upwards or downwards as they pass through the vacuum.
5. Particles with the correct velocity will pass through the window.



↑ B_{force}

↓ E_{force}

In a mass spectrometer, charged particles with the selected velocity will pass through the window and undergo circular motion, circling upwards with varying radii depending on mass. Different numbers of these charged particles will interact with different parts of the detector, and their abundances are proportional to generated current due to electron flow.

Electromagnetic Induction

Magnetic Flux

$$\Phi = BA \cos(\theta)$$

... where B is the magnetic flux density, A is the cross sectional area of the coil, and theta is the angle of the coil from the vertical of the cross section.

Flux linkage:

$$\Phi = NBA \cos(\theta)$$

... where N is the number of turns in the coil.

Faraday's Law

The EMF induced in a coil is equal to the rate of change of magnetic flux linkage.

$$E = -\frac{\Delta\Phi}{\Delta t}$$

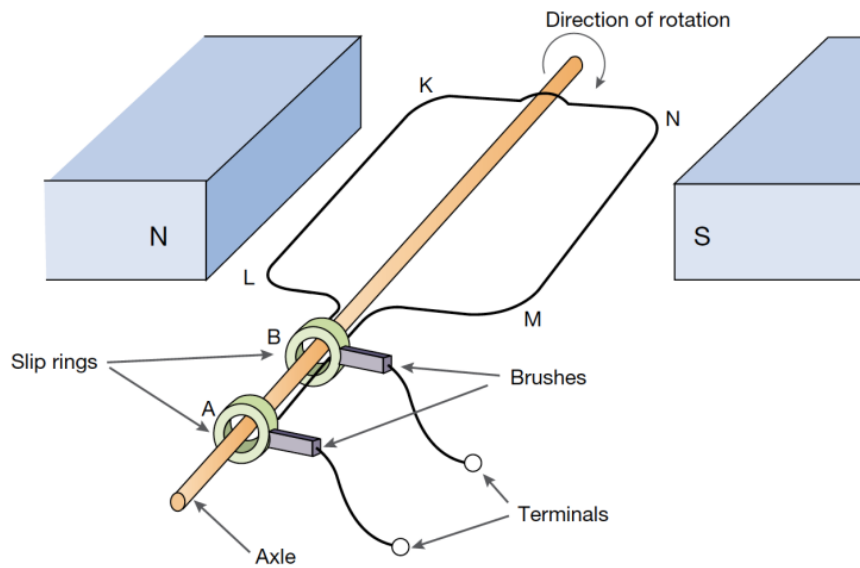
Lenz's Law

If the magnetic flux linkage through a coil changes, an emf is induced that drives a current whose magnetic field opposes the change in flux. This opposition is a consequence of conservation of energy.

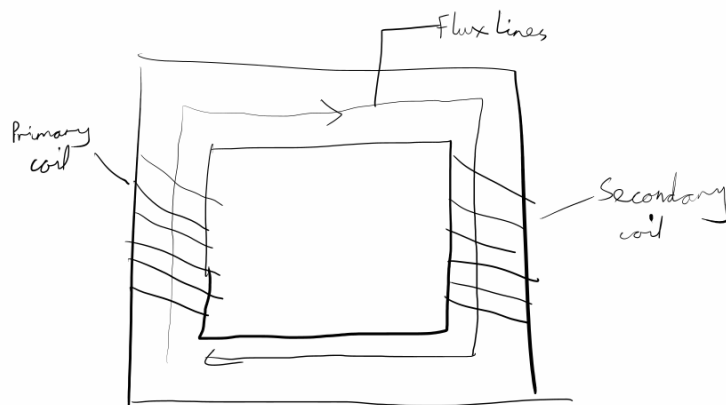
AC Generators

A coil of wire rotates inside a uniform magnetic field. Magnetic flux increases as it reaches 180 degrees, and decreases as it continues turning to 360 degrees. This alternating rate of change of magnetic flux linkage causes an alternating emf to be induced in the coil as per Faraday's law, causing an alternating current to be generated. As the coil rotates, slip rings also rotate with it, which interact with brushes (made from carbon and copper) to allow electrical contact from the slip rings to an external circuit. Contains:

- A permanent magnet
- A rectangular coil
- Slip rings
- Brushes



Transformers



An alternating current is passed through the primary coil, causing an alternating magnetic field to be generated, along with alternating magnetic flux lines through the soft iron core, which maximises retainment of magnetic flux lines due to magnetic shielding. This generates an alternating EMF in the secondary coil due to Faraday's law.

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

... where V_s and N_s are the EMF and number of turns in the secondary coil, and p is likewise for the primary coil.

Transformers can be >95% efficient, with some reaching over 99% efficiency.

An Eddy current can be created in the soft iron core due to the magnetic field from the primary coil. This creates an opposing magnetic field and releases energy into the core as heat, reducing efficiency. This is mitigated by laminating the transformer cores - i.e. making them made up of layers of iron stuck together instead of being one solid block of iron.

6.4 - Nuclear and Particle Physics

The Nuclear Atom

The alpha particle scattering experiment involved the firing of alpha particles at a thin sheet of gold foil. Due to the old belief in the plum-pudding model for the atom, it was expected that the alpha particles would pass straight through the sheet due to their momentum.

Actual observations:

- Most passed through.
- Some were deflected at an angle.
- Some reflected completely back towards the detector's direction.

Deductions:

- The atom is mostly empty space.
- The vast majority of the atom's mass is concentrated at the centre of the atom (the nucleus).
- There is a very small, concentrated point of positive charge at the centre of the atom (the nucleus).

Bohr's "nuclear model" of the atom involves electrons orbiting certain orbits/energy levels around a central nucleus (that contains the vast majority of the mass).

Isotopes are atoms of an element with the same number of protons but a different number of neutrons. The term **nuclide** refers to a specific species of atom. E.g. C-12 and C-14 are different isotopes of carbon, but a C-12 nuclide has two less neutrons than a C-14 nuclide.

The Strong Nuclear Force

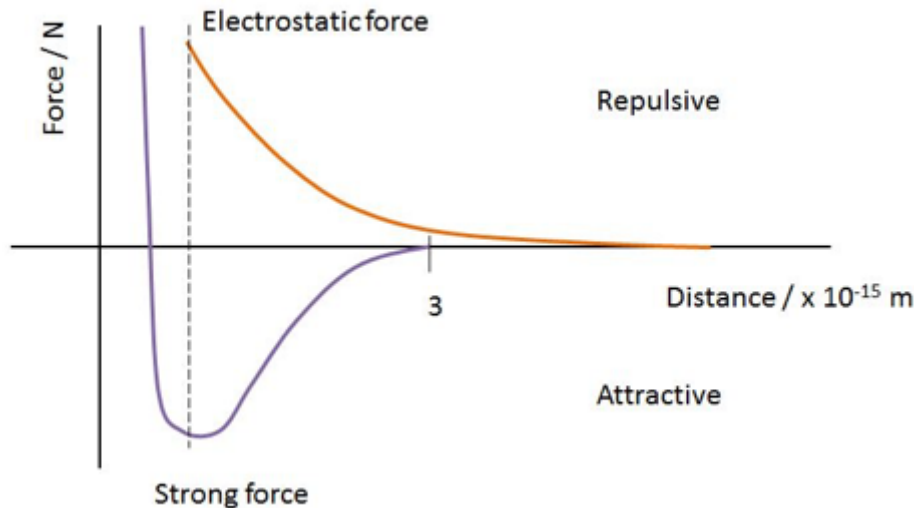
Using Coulomb's law, we can calculate the electric force between two protons at 3fm of separation:

$$F = \frac{Q^2}{4\pi\epsilon_0 r^2}$$

$$F = \frac{(1.6 \times 10^{-19})^2}{4\pi\epsilon_0 \times (3 \times 10^{-15})^2}$$
$$= 25.4N$$

This is an extremely large force for protons this close to each other. The gravitational force is far too small considering how low the mass of a proton is. The actual force counteracting this electric force is known as the strong nuclear force.

This force acts within the confines of the nucleus, but decreases rapidly with distance and does not extend much beyond adjacent protons and neutrons. The force must act between nucleons, and is independent of charge. At a particular distance, however, it turns from an attractive force to a repulsive force, otherwise the nucleus would collapse on itself:



The strong nuclear force, as you can see, stops acting just a little before 4fm of nucleon separation.

Nuclear Density

As the number of nucleons increases, the radius of an atom increases at a decreasing rate, reaching a constant-looking positive gradient on a radius x nucleon graph. The radius of a nucleus can be determined using:

$$R = r_0 A^{\frac{1}{3}}$$

... where r_0 is a constant and A is the nucleon number of the atom. r_0 is approximately $1.05\text{fm} = 1.05 \times 10^{-15}\text{m}$.

Nuclear density is equal to:

$$\rho = \frac{3m_n}{4\pi r_0^3}$$

... where m_n is the mass of a nucleon. Since all of these values are constants, **all nuclei have the same density.**

Fundamental Particles

- Hadrons are particles consisting of a combination of quarks to give a net zero or whole number charge, and can be subject to the strong nuclear force. E.g. neutrons and protons.
- Leptons are a type of fundamental particle. E.g. electrons and neutrinos. Each charged lepton has its own neutrino version, e.g. an electron neutrino or a muon neutrino.
- Quarks are fundamental particles that are components of hadrons. E.g. up and down quarks.
- The weak nuclear force is experienced by both quarks and leptons, and is responsible for beta decay due to the ability to change quarks' types and leptons' types.
- An antiparticle is a particle of antimatter that has the same rest mass as the original with an equal and opposite charge. When they collide with their original, they annihilate, turning into energy as per $E = mc^2$ as two gamma photons in opposite directions.

The three quarks that were initially proposed were called the "up", "down", and "strange" quarks:

	Quarks			Antiquarks		
Type	up	down	strange	anti-up	anti-down	anti-strange
Symbol	u	d	s	u bar	d bar	s bar
Charge Q	+2e/3	-1e/3	-1e/3	-2e/3	+1e/3	+1e/3
Strangeness S	0	0	-1	0	0	+1
Baryon number B	1/3	1/3	1/3	-1/3	-1/3	-1/3

We can use these quarks to see how certain particles and antiparticles are constructed:

Particle	Antiparticle
Proton: uud	Anti-Proton: u-bar d-bar d-bar
Neutron: udd	Anti-Neutron: u-bar u-bar d-bar

When a proton decays to a neutron, it just means an up quark of a proton decays to a down quark. Since the difference in charge of an up and down quark is -1e, an electron is released - beta minus decay.

Radioactivity

Radioactive decay is the spontaneous and random decay of an unstable nucleus by the emission of alpha, beta, and gamma radiation. The word "spontaneous" is used because decay is not affected by any external factors, such as temperature, pressure, chemical reactions, and magnetic fields. Neither the exact number of decays per second nor the fact that a particle will decay can be

estimated.

Type	Description
Alpha	• Release of a helium nucleus. • Low penetrating power. • Most ionising. Alpha decay example: ${}_{92}^{238}\text{U} \rightarrow {}_2^4\text{He} + {}_{90}^{234}\text{Th} + {}_0^0\gamma$
Beta	• Release of an electron+antineutrino or positron+neutrino. • High penetrating power. • Less ionising, but still dangerous. • 99% the speed of light. Beta minus decay example and quark equation (electron antineutrino, missing subscript e): ${}_{6}^{14}\text{C} \rightarrow {}_{-1}^0\text{e} + {}_7^{14}\text{N} + {}_0^0\bar{\nu}$ $d \rightarrow u + {}_{-1}^0\text{e} + {}_0^0\bar{\nu}$ Beta plus decay example and quark equation (electron neutrino, missing subscript e): ${}_{9}^{18}\text{F} \rightarrow {}_1^0\text{e} + {}_8^{18}\text{O} + {}_0^0\nu$ $u \rightarrow d + {}_1^0\text{e} + {}_0^0\nu$
Gamma	• Release of gamma photons. • Highest penetrating power. • Least ionising. • Usually accompanies either alpha or beta decay when a daughter nuclide is left in an excited state, but never occurs as a purely gamma decay.

Radioactive Decay Equations and Half Life

The activity dictates the number of nuclear decays per unit time. One decay per second is known as 1Bq (becquerel).

The decay constant lambda is the probability that an individual nucleus will decay per unit time.

$$\lambda = \frac{A}{N}$$

... where A is activity and N is the number of undecayed nuclei. The rate of change of undecayed nuclei is:

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

General decay equations for exponential decrease from initial values A_0 and N_0 are:

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

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

You can rearrange these using ln and log laws in order to find lambda using graphical methods.

A substance's half life is the amount of time taken for the activity of a substance or the number of undecayed nuclei to halve. Can be estimated with a Nxt graph. You can substitute $A = 0.5A_0$ into the above exponential equation to find the half life given the value of lambda.

Radioactive Dating

Carbon Dating

Organisms take in carbon dioxide from the atmosphere. A small fraction of carbon atoms in this CO_2 is the radioactive C-14 isotope of carbon rather than the normal C-12 isotope. Once an organism dies, it no longer takes in CO_2 , so the C-14 starts to decay into nitrogen.

The ratio of C-14 to C-12 decreases over time, and can be compared with the ration of a currently living organism to estimate the age of the organism/object.

However, since the amount of C-14 is so small, count rates are also very small, and after a few half lives may be indistinguishable from the background count rate. It also assumes the ratio of C-14 to C-12 in the atmosphere has always been constant, which may not be true.

Dating Rocks

All rocks contain tiny amounts of radioactive isotopes such as U-238 and Ru-87, which have very long half lives. Relative proportions of the parent atoms and decay products can be used to estimate age.

Generating Energy

Nuclear Fission

Nuclear fission is when a radioactive nucleus absorbs a high-energy neutron, causing it to split into two more-stable nuclei and release 2-3 high-energy neutrons and gamma radiation. (Extra: Energy also comes from KE of daughter nuclei, which collide with moderator particles to transfer energy.)

e.g. uranium 235 (insert example here)

A nuclear fission reactor consists of a solid concrete wall, a moderator, and a reaction chamber in the moderator. Inside the reaction chamber, there are numerous control rods and pills containing the radioactive substance.

(diagram here)

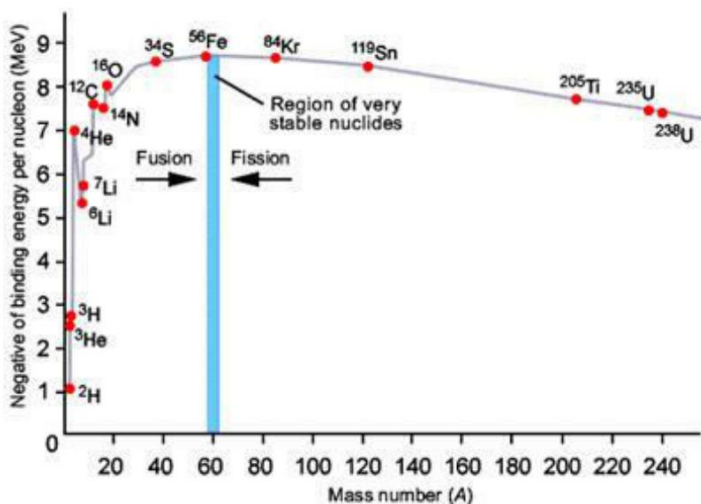
- The concrete wall ensures that radiation cannot escape the reaction chamber, keeping employees safe from radiation exposure.
- The moderator reduces the speed of high-energy neutrons so that they can be absorbed by nuclei. (There was another advantage)
- The control rods are made of a material such as boron, and exist to absorb excess high-energy neutrons. This is to keep control of the chain reaction. Losing control leads to reactor meltdowns such as Chernobyl.

Nuclear Fusion

Nuclear fusion is when two nuclei are fused together, releasing energy based on the difference in binding energy of the product and the total binding energy of the constituent nuclei.

Binding energy is the minimum energy required to separate the nucleons to infinity.

The binding energy curve

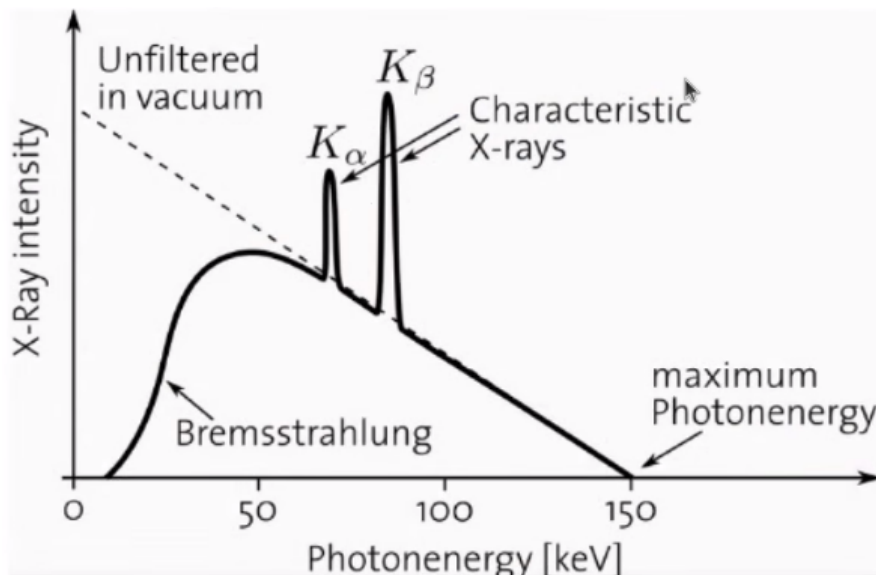


e.g. there is an increase from H-1 to H-2, meaning it releases ~1,7MeV of energy on fusion.

6.5 - Medical Imaging

Xray production

Electrons are emitted into a vacuum tube via thermionic emission. An external power supply produces a massive p.d. between the anode and cathode, causing the electrons to be rapidly accelerated in this high-voltage electric field. Then they are rapidly decelerated with collisions with a hard metal anode, causing them to lose KE ($\sim 1\%$) which is emitted as xrays. Rest is lost to the anode as thermal energy. Their KE is transformed into high-frequency photons of EM radiation. This radiation is called Bremsstrahlung radiation. The below graph shows an example of x-ray energy distribution.



The spikes, known as Characteristic X-rays, occur when a high-speed projectile electron knocks an inner-shell electron out of a target atom, creating a vacancy. To stabilize the atom, an electron from a higher-energy outer shell drops down to fill this hole, releasing a photon with an energy exactly equal to the difference between those two specific shells. Because these atomic energy levels are unique and discrete for every element, the resulting X-rays appear as sharp, high-intensity peaks at specific energy values rather than a continuous spread. This makes the spikes a "spectral fingerprint" of the specific metal used in the xray tube's anode.

Xray focusing

Straight, parallel xrays are created by directing xrays to a thin window which enters a collimator that absorbs xrays that are not parallel to it. Xray energy is absorbed by tissue as it passes through

the body, and how effective this absorption is depends on the attenuation coefficient μ , which is constant for different materials. The energy before entering and after exiting the body can be measured. These differences can be visualised on photographic film or a digital image to view the targeted body part.

Xray attenuation

"Exponential decay"-like formula for xray intensity loss:

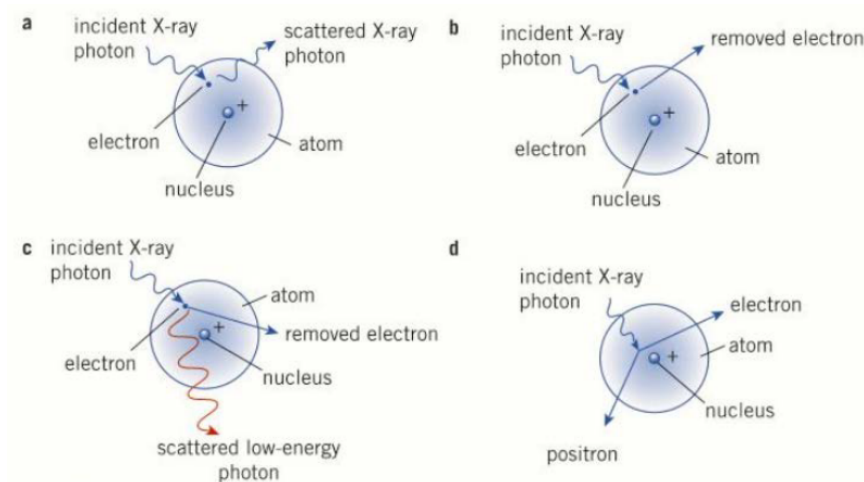
$$I = I_0 e^{-\mu x}$$

- I = Intensity
- I_0 = Initial intensity
- μ = Attenuation coefficient
- x = Distance traveled through body

$\mu \propto z^3$

... where z is the proton number of the material.

Attenuation mechanisms



Simple Scattering (a)

Simple scattering is when xray photons reflect off of bone if they do not have sufficient energy to do more complex scattering.

Photoelectric Effect (b)

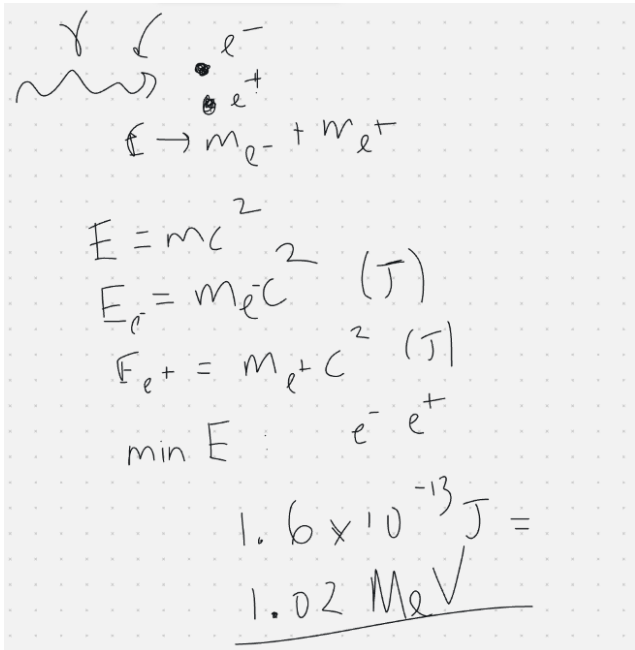
Via the photoelectric effect, xray photons are absorbed by electrons into the material, releasing photoelectrons.

Compton effect (c)

In the Compton effect, a photon interacts inelastically with an electron. The photon transfers some of its energy and momentum to the electron. The photon is scattered with **less energy**, while the electron is removed from the atom. Both energy and momentum are conserved in this interaction.

Pair Production (d)

Pair production is when an electron-positron pair is spontaneously created as the xray passes through the electric field of an atom. The required energy is about 1.02MeV, as derived below:



$$E \rightarrow m_{e^-} + m_{e^+}$$

$$E = mc^2$$

$$E_{e^-} = m_{e^-} c^2 \text{ (J)}$$

$$E_{e^+} = m_{e^+} c^2 \text{ (J)}$$

$$\text{min } E : e^- e^+$$

$$1.6 \times 10^{-13} \text{ J} =$$

$$\underline{1.02 \text{ MeV}}$$

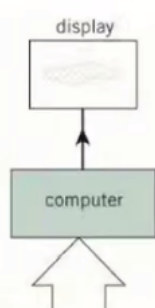
Not very applicable in medical imaging, as xrays usually don't have this much energy.

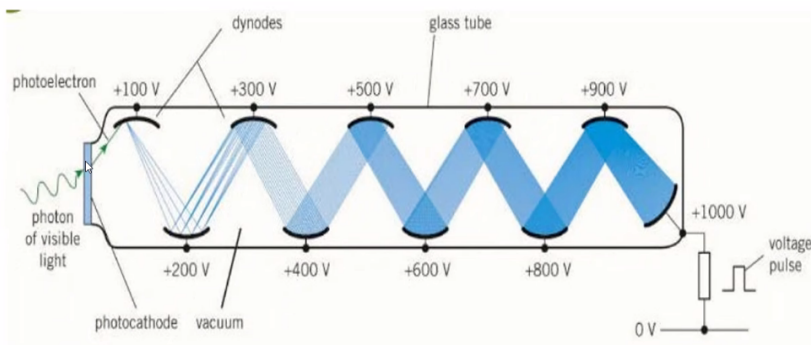
Medical Tracers

Medical tracers are substances injected into a body. Their position in the body can be detected.

- Fluorine-18 for beta+ decay. Protons decay into neutrons, releasing a positron and an electron-neutrino. The positron annihilates with an electron, releasing two gamma photons travelling in exactly opposite directions which are detected.
- Technetium-99m decays to immediately release gamma photons. Primarily used to monitor major organs. The "m" means metastable, meaning it remains in a high energy state for prolonged periods of time, eventually decaying to a far more stable isotope of technetium.

Gamma detection





1. Gamma photons pass through the collimator if their direction of travel is parallel to it. Otherwise, they are absorbed by it.
2. These high-energy photons interact with the scintillator, releasing multiple more lower energy photons (usually visible light).
3. The light guide/photocathode absorbs the photons and releases photoelectrons via the photoelectric effect.
4. These electrons travel through the photomultiplier tube, generating more electrons to be passed into a computer for imaging.

In the photomultiplier tube, a photoelectron hits the first plate, releasing more electrons that hit the next plate, which causes more electrons to be released to hit the next plate. This repeats, generating lots of electrons that can create a substantial current.

CAT Scans

Uses xrays to create a 3-dimensional image of a person's body.

The machine is a ring that the person's body passes through. It generates a fan shaped beam of xrays to take 2d slices of the person's body, which are picked up by a ring of electronic detectors. The images are stacked on top of each other in a computer program to create the 3D product.

The resolution of the image is greater and can distinguish between different soft tissues, which 2D xrays cannot do.

However, it takes significantly longer than a 2D xray, so the patient is exposed to a higher dose of ionising radiation. About 10-30 minutes.

PET Scans

PET scans detect gamma rays generated from annihilation between positrons and electrons to create a 2D or 3D image. It has a ring of gamma detectors/cameras that pass up and down the patient to generate a 3D image.

Positron-electron annihilation releases two photons in opposite directions. The ring can pick up both of these and use the time delay between their arrivals to calculate the exact location of the annihilation event, characterising the depth inside the body. This means PET scans have a higher resolution than other gamma cameras.

Ultrasound

A high frequency longitudinal wave of >20kHz.

(A piezoelectric material generates a voltage when it is contracted or expanded, or **will contract and expand when a voltage is applied**.) Applying an alternating voltage to a piezoelectric crystal causes it to contract and expand at the same frequency as the alternating source, producing ultrasound waves.

An ultrasound transducer has an alternating potential difference causing repetitive compression and stretching of the crystal. The crystal's resonant frequency is chosen to increase intensity. After creation of the ultrasound, the potential difference is removed and the reflected signal is read.

- An A type ultrasound scan produces a very low resolution 1D image. It is used to determine distances from the ultrasound device to the point of reflection. This is achieved by measuring time delay between generating and receiving the signal, using the speed of sound to approximate distance.
- A B type ultrasound scan produces a 2D image by moving the transducer over the patient's skin. It is effectively a series of A type scans stitched together to form an image.

$$Z = \rho c$$

... where Z is acoustic impedance, rho is the density, and c is the speed of sound in the material.

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

I_r is the intensity of reflected ultrasound. I_0 is the intensity of incoming ultrasound. The ratio is known as the reflection coefficient.

A gel is put on the skin before an ultrasound. It has a similar acoustic impedance to skin to minimise the amount of reflected ultrasound waves.

The Doppler Effect

The Doppler effect is the observed change in the frequency of a wave when it is reflected off of or produced by a moving source, e.g. an ambulance siren.

$$\Delta f = \frac{2fv\cos\theta}{c}$$

... where delta f is the observed shift in frequency, f is the original frequency, v is the speed of blood flow, theta is the angle between the probe and blood flow direction, and c is the speed of

ultrasound in blood.