Physics AS - Unit 1 - Particles, Quantum Phenomena and Electricity - Revision Notes

Particle Physics

Inside the Atom

- Electron (negatively charged) in shells and subshells around nucleus
- Nucleus composing of protons (positively charged) and neutrons
- **Nucleons –** protons and neutrons
- **Coulomb (C) –** Unit of charge equal to the electrical charge transferred by a steady current of 1 Ampere in 1 Second
- **Elementary Charge (*e*) -** Electric charge carried by a proton or equivalently the absolute value of the electric charge carried by a electron (as electron is negatively charged)

$$e = 1.602176487\times10^{-19}$$

Particle	Relative Mass	Absolute Mass (Kg)	Relative Charge	Absolute Charge (C)
Proton	1	$1.67\text{x}10^{-27}$	+1	$+1.60\text{x}10^{-19}$
Neutron	1	$1.67\text{x}10^{-27}$	0	0
Electron	Negligible	$9.11\text{x}10^{-31}$	-1	$-1.60\text{x}10^{-19}$

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

A = Mass number/Nucleon Number
Z = Atomic Number (Number of protons)

- **Isotope -** an atom with the same number of protons (Atomic number) but a different number of neutrons (mass number).
- Each different type of nucleus is known as a **Nuclide**

Specific Charge

- **Specific Charge –** Charge of a specific particle divided by its mass

  Nucleus of ${}^{1}_{1}H$ has a charge of $+1.60\text{x}10^{19}$ C and mass of $1.67\text{x}10^{-27}$ Kg hence its specific charge = $9.58\text{x}10^{7}\text{CKg}^{-1}$

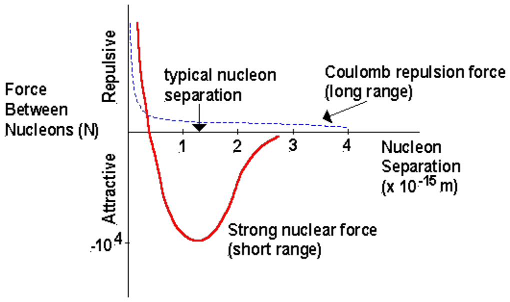
Fundamental Forces

- Current theories suggest that there are only four types of interaction in the universe between particles:
  - **Gravity –** This force acts between **all** particles in the universe and has an infinite range (however reduces in strength according the inverse square law). At an atomic scale it has negligible influence, as it is the weakest fundamental force in the universe. Gravitation is **mediated by the graviton** (undiscovered)
  - **Electromagnetic Force –** This force acts between **any charged particles.** It can either be repulsive (same charge) or attractive (different charges). The electromagnetic force is responsible for keeping molecules together. The electromagnetic force is **mediated by virtual photons**
  - **Weak Interaction –** This force acts on all known fermions or rather all particle with a ½ integer spin (quarks, leptons and baryons but not bosons- elemental bosons and baryons). The weak interaction acts over a very short range (roughly an atto-meter $1\text{x}10^{-18}$). Over this range it is many times stronger than gravitation (roughly 10^{33}). The weak interaction is responsible for

electromagnetic decay. The weak interaction is **mediated by W and Z Bosons** (elemental particles)

  - **Strong Interaction –** This force is observable in two areas. On the smaller scale the strong interaction is responsible for holding quarks together in hadrons, on the larger scale it binds protons and neutrons together inside the atomic nucleolus (when talked about in terms of binding protons and neutrons together it is referred to as the strong nuclear force or the residual strong force). The strong force **binding quarks together is mediated by gluons**, while the **mediator responsible for binding protons and neutrons together is the Pion or Pi Meson**

Strong Nuclear Force *(Residual Strong Force)*



- Overcomes the electrostatic repulsion between
- Keeps the nucleus stable
- Attractive between 4-0.4fm (Femto-Metre = 1x10^{-15} m) and repulsive below 0.5fm (otherwise the nucleus would collapse and be point like)
- Keep all nucleons together not just protons
- The mediators of the nuclear force are Pions or Pi Mesons (π^0)
- Also called the residual strong force (as the strong nuclear is related to the strong force), the strong nuclear force is responsible for keeping nucleons together while the strong force is responsible for keeping quarks together (mediator – Gluons)

Radioactive decay

Alpha Decay

- Release alpha particles (positively charged helium ions)

$$ {}_{2}^{4}\alpha^{2+} $$

- Reduces mass number of a nucleus by 4 and atomic number by 2 hence:

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

Beta Decay

- 2 types of Beta Radiation: β^+ and β^-

β^+ Decay (positron)

- Proton decays into a neutron emitting an electron neutrino and a positron:

$$ p \rightarrow n + v_e + e^+ $$

β^- Decay

- Neutron decays into a proton emitting an electron and an electron anti-neutrino:

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

Note: bar above electron neutrino indicated that it is the anti-particle counterpart, the electron does not follow this rule and instead the positron is shown by a change of charge

Gamma Radiation

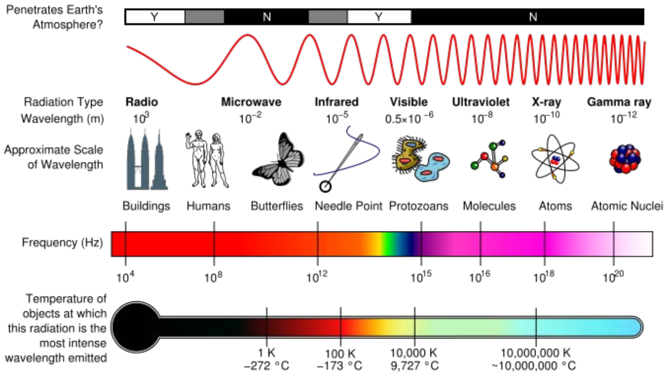
- When alpha or beta decay occurs the nucleus is usually left in an excited state it subsequently releases a high energy photon (gamma particle) to reduce this energy
- Photon γ - no mass and no charge

Electromagnetic Waves - Photons

- The speed of the wave is given by: $c = f\lambda$
- Frequency by: $\frac{c}{\lambda} = f$
- Photons are emitted when:
  - Fast moving electron stopped
  - Electron "jumps" from higher quantum level (shell) in an atom to a lower one
- The energy of a electron can be given by:

$$E = hf$$

Note: where h = Planck's constant 6.63x10^{-34}



As $c = f\lambda$ this can also can be shown as:

$$E = \frac{hc}{\lambda}$$

- A laser beam consists of photons of the same frequency hence it can be shown that:

$$E = nhf$$

Particles and Anti-Particles

- When a particle and its corresponding anti-particle meet they annihilate and are converted completely into energy (found by E=mc^2)
- It is also possible for a photon of a high enough energy to spontaneously change to a particle and its anti-particle counterpart; this is known as Pair production
- Energy of a particle is usually measure in Mev (millions of electron volts) and is defined as the energy required to accelerate an electron through the potential difference of 1 volt. 1 Mev = 1.60x10^{-13}J
- **Anti-particles:**
  - Same rest mass as corresponding particle
  - Same rest energy as corresponding particles
  - Opposite charge (if the corresponding particle has charge)

Note: Antiparticles are usually denoted with a line above ($\overline{V}_e$ is an electron anti-neutrino) with the exception of the positron (anti-electron), which is denoted by e^+

- Rest Energy (energy when stationary) of a particle can be found by $E = mc^2$, where m is the mass of the particle when stationary and c is the speed of light

Pair production

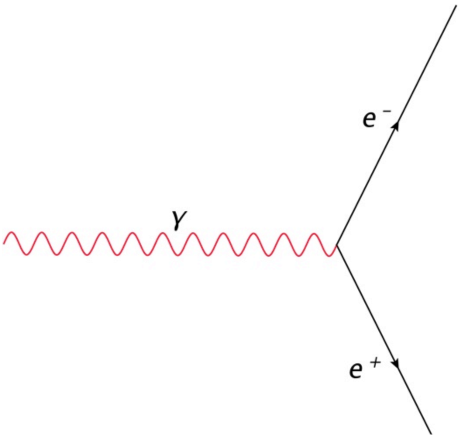
- This occurs when a photon with a high enough energy changes into a particle and its corresponding anti-particle
- As one photon turns into 2 particles, using E=mc^2, the photon must have at least the rest energy of the 2 particles that it turns into, hence:

$$E_0 = mc^2$$

As 2 particles are produced

$$2E_0 = 2(mc^2)$$

Therefor the energy of the photon must be:



Pair Production Diagram (not Feynman diagram)

$$E_{\gamma} = 2E_0$$

$$as\ E = hf$$

$$hf = 2E_0$$

Annihilation

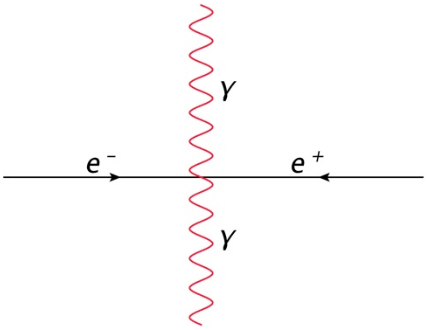
- This occurs when a particle and its corresponding anti-particle meet and convert themselves to energy in the form of 2 photons as seen in diagram.
- As 2 photons are produced using the equations above it can be shown:

$$2E_{\gamma} = 2E_0$$

Hence:

$$E = mc^2$$

$$hf = E_0$$



Annihilation Diagram (not Feynman diagram)

Particle Interaction

Electromagnetic Force

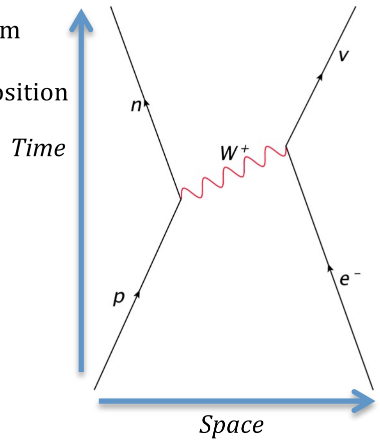
- Occurs only between charged particles:
  - Opposite charges attract
  - Same charges repel
- The **Mediators** of the force are virtual photons; they are called so as we cannot directly detect them as if we did we would stop the force from occurring.

Weak Nuclear Force

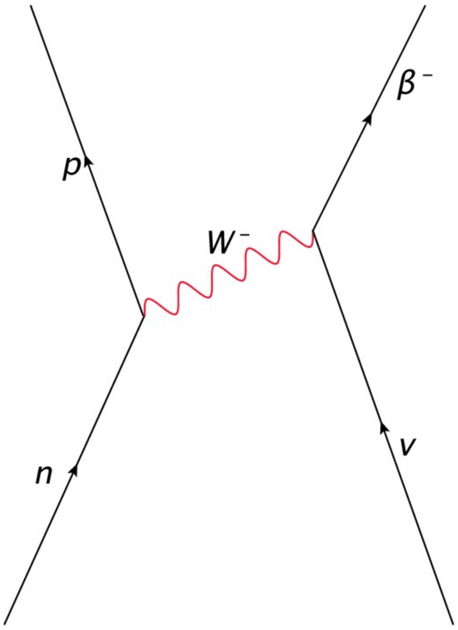
- Responsible for Beta decay (both types)
- Weak interaction only occurs with leptons and hadrons, this explains why neutrinos are so reluctant to react with anything
- The **Mediators** of this force are bosons of which there are 3 types: W^+ W^- and Z, The W bosons are each others respective anti-particle (opposite charges) while the Z boson is its own and subsequently has no charge (Z bosons are not covered in the specification).
- **W Bosons:**
  - Non-zero rest mass
  - Short range; Bosons are relatively massive and consequently are high in energy which means they have a short lifetime which leads to them only being able to act over small distances (typically 10^{-17}m)

Feynman Diagrams

- Particle interactions and decays can be represented visually by the means of a Feynman diagram (names after Richard P. Feynman)
- The interaction is represented on the diagram as followed:
    - Following from the bottom to the top of the diagram shows the interaction's/decay's change with time
    - The other axis (left to right) shows the particles position in space at any given time

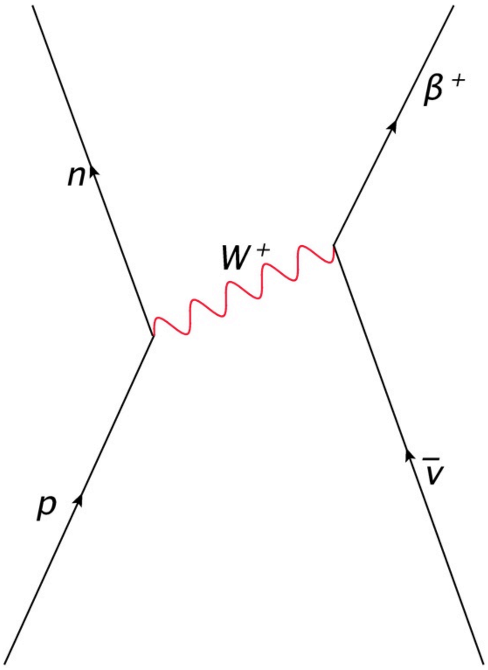


Neutron-Neutrino Interaction

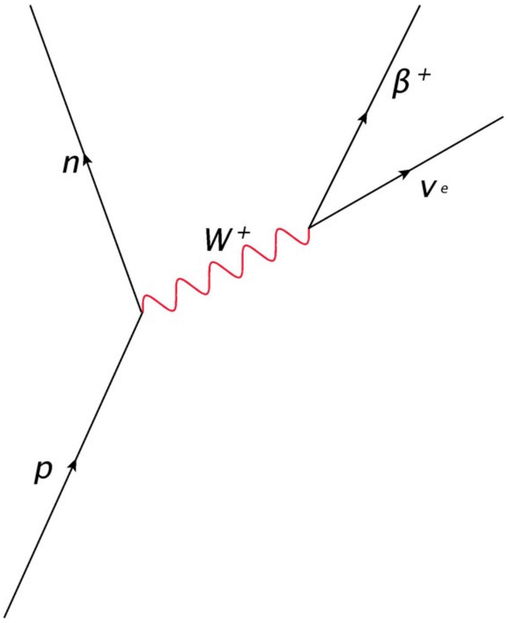


Note: Mediator (W Boson) is either positively or negatively charged depending upon on the charge change of the particles involved

Proton-Anti-Neutrino Interaction

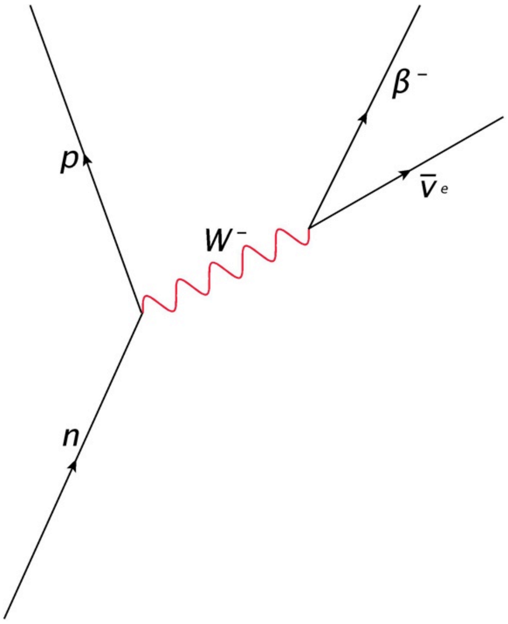


Beta Plus Decay



Note: the W^+ boson decays into a β^+ and a Electron Neutrino

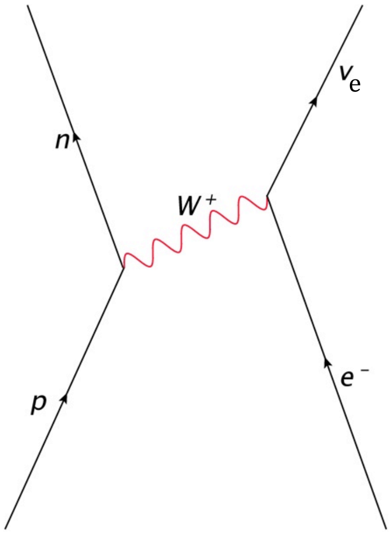
Beta Minus Decay



Note: the W^- boson decays into a β^- and a Electron Anti-Neutrino

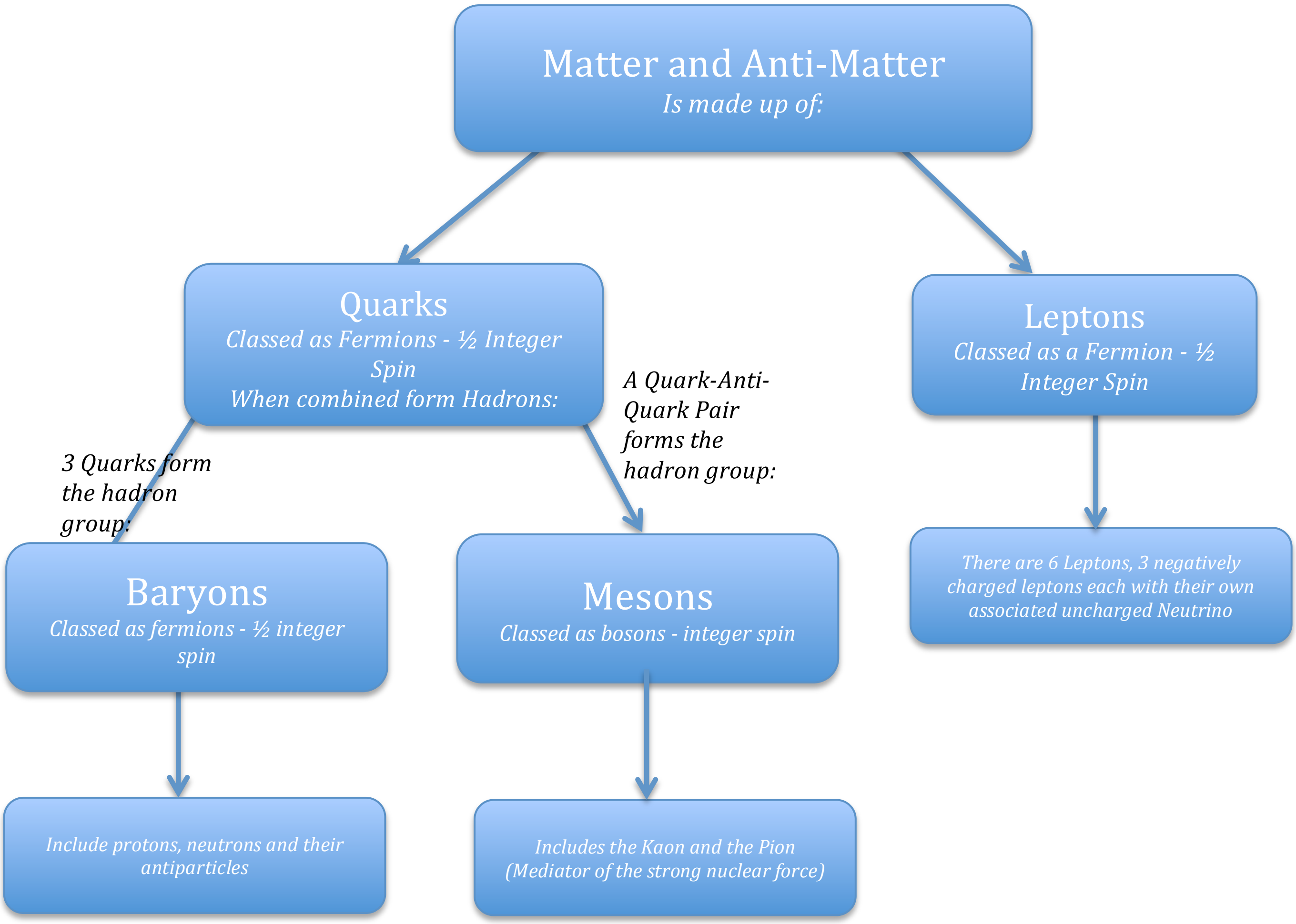
Electron (K or L) Capture

- This occurs when a proton rich nucleus turns a proton into a neutron by capturing an electron from the K or L shell (1st and 2nd shell respectively)
- This process can also occur when a proton and an electron collide however if the electron has sufficient energy a different interaction will occur where a W^- Boson is exchanged from the electron to the proton



Classification of Particles

- We can classify all types of particles according to their spin: (spin is a characteristic property of elemental particles; just as charge is):
  - **Fermions**
    - Have half-integer spin, i.e. a multiple of $\frac{1}{2}$
    - Can be a elementary or composite particle (composite particles are made up of a number of elementary particles)
    - All known fermions are Dirac fermions, that is for every particle there is a distinct anti-particle (a particle with certain opposite properties such as charge)
    - Fermions are the basic "building blocks" of matter – they make up protons and neutrons and include electrons which together is the composition of atoms
    - 12 types of fermions (ignoring anti-particles), 6 quarks and six leptons
  - **Bosons**
    - Have integer spin
    - The fundamental forces of nature (electromagnetism, strong and weak interaction and gravitation) are called gauge bosons
    - Can be a elementary or composite particle (composite particles are made up of a number of elementary particles)



Elementary Particles

- **Elementary particles –** are fundamental particles that have no internal structure, they are the "building blocks" of everything, just as we think of elements as "building blocks" of molecules
- Elementary particles can be separated into either bosons or mesons (depending upon their spin) as we saw above mesons have half integer spin while bosons have whole integer spin
- We can their for split the elementary particles dependent upon if they are bosons or mesons:
    - **Fermions – 2 Separate types of Elemental Fermion:**
        - Quarks (6 types and 6 corresponding anti-particles)
        - Leptons (6 types and 6 corresponding anti-particles)
    - **Bosons – 1 type of Elemental Boson:**
        - There are 6 elemental bosons and they are just referred to as bosons
        - The fundamental forces of nature (electromagnetism, strong and weak interaction and gravitation) are mediated by a special group of elemental bosons referred to as gauge bosons

Fermions

- Made up of 6 leptons and 6 quarks (and their corresponding antiparticle)

Leptons

- Leptons are fundamental particles with no internal structure
- They are not effected by the strong interaction
- Have half integer spin
- The leptons respective antiparticles are the **antileptons** which are identical expect for the fact they carry the **opposite electrical charge** and **opposite lepton number**
- There are 6 leptons in total, the three charged leptons are called **electron-like leptons** while the neutral leptons are called **neutrinos**
- The leptons and some characteristic properties:

Particle	**Symbol**	**Charge** **(In terms of elemental charge)**	**Mass** **(In terms of the electron)**	**Lepton Number**	**Lepton Electron Number**	**Lepton Muon Number**	**Lepton Tau Number**
Electron	e	-1	1	+1	+1	0	0
Electron Neutrino	V_e	0	Near Zero	+1	+1	0	0
Muon	μ	-1	207	+1	0	+1	0
Muon Neutrino	V_μ	0	Near Zero	+1	0	+1	0
Tau	τ	-1	3500	+1	0	0	+1
Tau Neutrino	V_τ	0	Near Zero	+1	0	0	+1

Note: All neutrinos have no charge, and all other leptons have charge of -1 (relative to e)

- Although a table of lepton number will be given in the exam remember that all leptons have a lepton number of +1 and all anti-leptons have a lepton number of -1, the electron and the electron neutrino have an electron lepton number of +1 while their anti-particle counter-parts have an electron number of -1 (this also applies in the same way the muon and tau lepton number)

Quarks

- The building blocks of all hadrons (composite particles – ones made out of a combination of fundamental)
- Have half-integer spin
- Quarks can never be found by themselves due to colour confinement (based upon another characteristic property: colour)
- The quarks and some characteristic properties:

Name	**Symbol**	**Anti-Particle**	**Charge** (In terms of elemental charge)	**Mass (MeV/c²)**	**Baryon Number**	**Strangeness**
Up	u	$\bar{u}$	$+\frac{2}{3}$	1.5-3.3	$+\frac{1}{3}$	0
Down	d	$\bar{d}$	$-\frac{1}{3}$	3.4-6.0	$+\frac{1}{3}$	0
Charm	c	$\bar{c}$	$+\frac{2}{3}$	1160-1340	$+\frac{1}{3}$	0
Strange	s	$\bar{s}$	$-\frac{1}{3}$	70-130	$+\frac{1}{3}$	-1 (+1 for $\bar{s}$)
Top	t	$\bar{t}$	$+\frac{2}{3}$	169100-173330	$+\frac{1}{3}$	0
Bottom	b	$\bar{b}$	$-\frac{1}{3}$	4130-4370	$+\frac{1}{3}$	0

- All of the associated anti-quarks have opposite charge, baryon number and strangeness
- Up and down quarks have the lowest masses and the other quarks rapidly change into up and down quarks
- Note: only up down and strange quark characteristics needed for exam

Bosons

- Mediator particles (ones that are exchange particles for the fundamental forces of nature) are called gauge bosons
- The bosons and some characteristic properties:

Particle	**Symbol**	**Anti-Particle**	**Charge** (In terms of elemental charge)	**Interaction Mediated**	**Existence**
Photon	γ	Self	0	Electromagnetic (Virtual Photon)	Confirmed
W Boson	W^-	$+\frac{1}{3}$	-1 (W^+ +1)	Weak Interaction	Confirmed
Z Boson	Z	Self	0	Weak Interactions	Confirmed
Higgs Boson	H^0	Self	0	None	Unconfirmed
Gluon	g	Self	0	Strong Interaction	Confirmed
Graviton	G	Self	0	Gravitation	Unconfirmed

Note: Only boson to have an antiparticle is the W boson

Composite Particles

- Composite particles are particles that are made out of other elemental particles bound together, protons and neutrons are composite particles as are atoms and even molecules

Hadrons

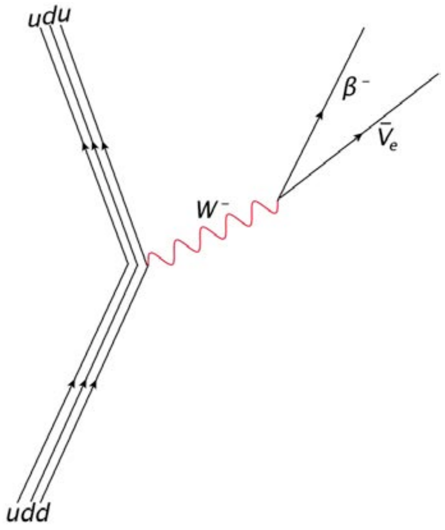
- Hadrons are strong-interacting composite particles
- Hadrons are either:
    - Composite fermions (half integer spin), these are called baryons
    - Composite bosons (integer spin), these are called mesons
- All known hadrons are composed of quarks and antiquarks

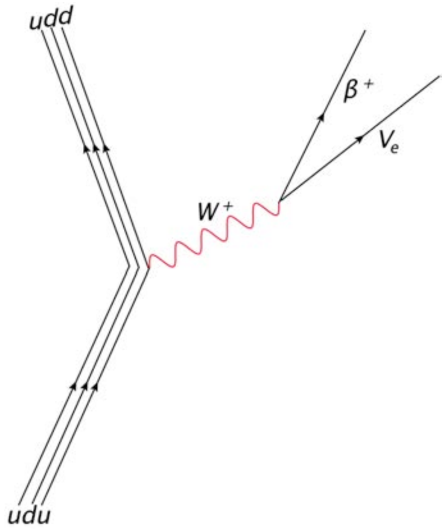
Baryons (fermions)

- Baryons have half integer spin
- They are made up of three quarks (held together by the strong force)
- Anti-Baryons are made up of the anti-particle partners of the respective quarks in the normal baryon
- As every quark has a baryon number of $+\frac{1}{3}$, any baryon has a baryon number of +1 (as a baryon is made up of 3 quarks). Likewise an anti-quark has a baryon number of $-\frac{1}{3}$, therefor an anti-baryon has a baryon number of -1 (as made up of 3 anti-quarks)
- **A Proton –** has 2 up quarks and a down quark shown by uud
- **A Neutron –** has 2 down quarks and an up quark udd
- **An Anti-Proton –** has 2 anti-up quarks and one anti-down quark $\overline{u}\overline{d}\overline{d}$
- The proton is the only stable baryon, even a *free* neutron (outside an nucleus) decays into a proton releasing an electron and an electron anti-neutrino as in β^-

Quarks and Beta Decay

- In the exam may be expected to represent β^- or β^+ with regard to quark change apposed to baryon change
- As stated before β^- is a neutron decaying into a proton with the emission of an electron and a anti-electron neutrino, in this decay a down quark is turning into an up quark which changes the quark composition from udd (a neutron) to uud (a proton). This change in quark composition can be represented in the Feynman diagram to the right





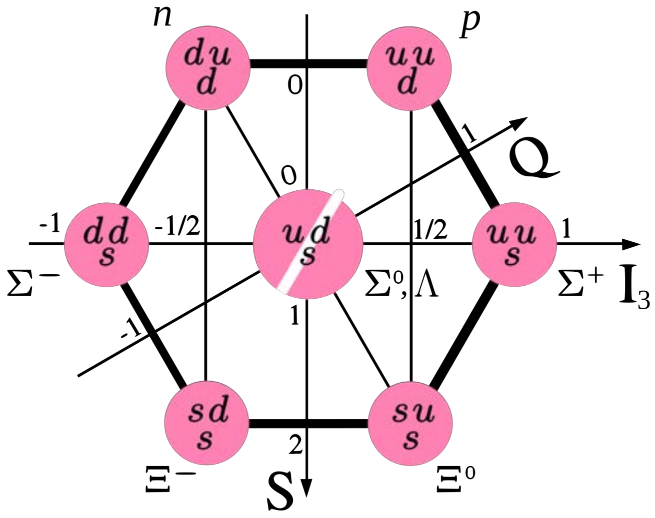
β^+ decay is a proton decaying into a neutron emitting a position and an electron neutrino. In this decay an up quark changes into a down quark. This changes the quark composition from uud (a proton) to udd (a neutron). This change in quark composition can be represented in the Feynman diagram to the left

Evidence for Three-Quark Model

- The first evidence for the three quark model (three quarks being combined to make a normal composite fermion) was in the Stanford linear accelerator
- The electrons collide at high speed with protons, the results showed that the electrons were scattered by three scattering centres in each atom

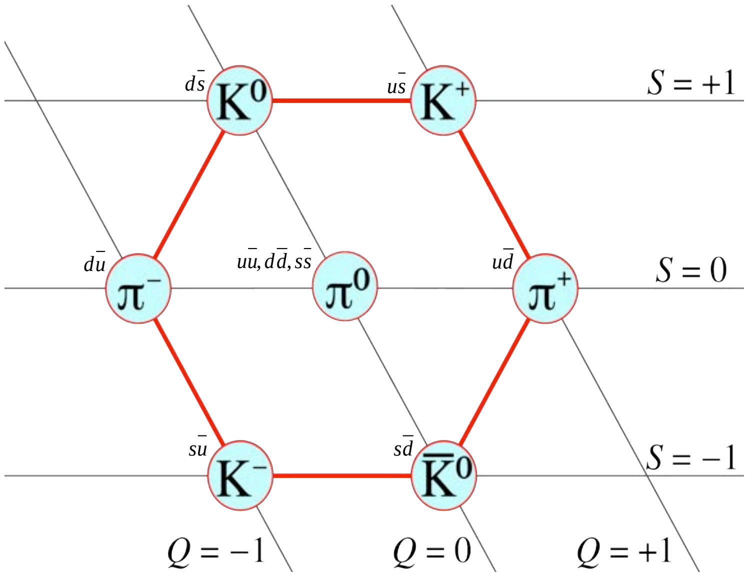
Baryon Octet (Eightfold way)

- The family of baryons with ½ spin composed of the up, down and strange quarks can be represented in a Octet:
- The Σ^0 and Λ particles differ only in energy



Mesons (bosons)

- Mesons have integer spin and are therefor bosons
- There are made up of more than one elemental particles and are therefor composite bosons
- Mesons are made up of one quark and one anti-quark
- The family of mesons with spin=0 can be represented in a nonet seen to the right
- The K series of mesons are known as the Kaons
- The π of series are known as the Pions
- Notice that there 3 uncharged mesons ($K^0, \overline{K}^0, \pi^0$)
- For the exam the pion and kaon composition is needed to be known



Conservation Rules

- All particles obey certain conservation rules when they interact.

Conservation of Energy

- As in all changes in science, not juts particle interactions and decays, the amount of energy remains fixed in a system
- This also applies to the “rest energy” of a particle (energy may be seen to have been lost however this “lost” energy may have been converted into mass following the rule $E = mc^2$
- No exceptions have been found for this law

Conservation of Charge

- In any interaction or decay the total of the charges of the particles before the interaction or decay is the same as the total of the charges of the particles afterwards
- No exceptions have been found to this law

Conservations of Lepton Number

- In any change, the total lepton number for each lepton branch before the change is equal to the total lepton number for that branch after the change
- All leptons have lepton number +1
- All anti-leptons have lepton number -1
- Conservation of the branch of lepton also applies:
  - Lepton electron, muon and tau number is always conserved
  - This can be useful to find out which type of neutrinos are emitted during certain decays

Conservation of Strangeness

- In any **strong interaction** strangeness is always conserved
- The total of all the strangeness of the particles before the change is equal to the total strangeness of the particles after the change
- It is not conserved however when the weak interaction is involved

Conservation of Baryon Number

- In any change the baryon number before the change is equal to the lepton number after the change
- All baryons have baryon number +1
- All anti-baryons have baryon number -1
- All mesons or leptons have baryon number 0
- This can be also thought of through quark change as each quark has baryon number +1/3

Quantum Phenomena

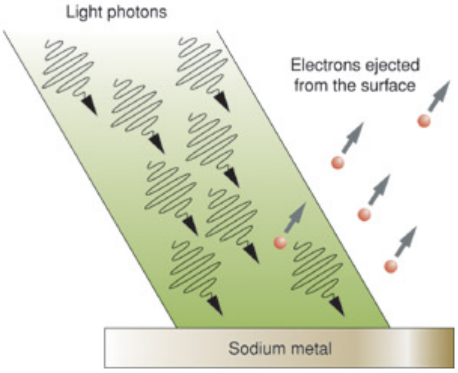
Electromagnetic Waves

- The electric and magnetic fields are perpendicular both to each other and the direction of propagation of the particle
- There is no need for a medium for an electromagnetic wave to travel through
- **Wavelength –** Defined as the distance between two adjacent points in phase in a wave
- **Period –** The period of a wave is defined as the time taken for one whole wave to pass a point through space:
- $P = \frac{1}{f}$
- **Wave Speed –** Speed of the waves is equal to distance travelled by wave in one cycle divided by time taken for one cycle

$$C = \frac{\lambda}{1/f} \text{ Therefor } c = f\lambda$$

The Photoelectric Effect

- The photoelectric effect is a type of quantum phenomena that shows that light can behave as a particle as well as a wave (the photoelectric effect can only be explained with regards to light acting as particles or "Quanta" of energy)



- Experiments showed that when light was shone on a metal electrons could be emitted from the surface of metal however the emission of these electrons were dependent on several factors:
    - Photoelectric emission of electrons from a metal surface does not take place if the frequency of the incident electromagnetic radiation is below a certain value known as the **threshold frequency.** The threshold frequency is dependent on the type of metal used

      Note: as $c = f\lambda$ the wavelength of that incident light has to below a maximum value
    - The number of electrons emitted per second is proportional to the intensity of the electromagnetic radiation as long as the frequency of that electromagnetic radiation is above the threshold frequency as discussed before
    - Photoelectric emission occurs instantaneously provided the frequency of the incident electromagnetic radiation is above the threshold frequency

Explanation of the Photoelectric Effect – The Photon Model of Light

- Electromagnetic radiation consists of packets (quanta) of energy, known as photons. The energy of each photon can be found using the following formula:

$$E = hf$$

where h = Planck's constant $6.63\text{x}10^{-34}$ *and f is the frequency of the electromagnetic radiation*

- When light is incident on a metal surface, an electron at the surface absorbs a **single** photon from the incident light and therefore gains energy equal to *hf,* as calculated using the formula above

- An electron can leave the metal surface if the energy gained from the single photon exceeds the **work function,** ϕ , of the metal. This is the minimum energy needed for an electron to escape from the metal's surface
- Hence it can be seen that the maximum kinetic energy of an emitted electron follows:

$$E_{k(Max)} = hf - \phi$$

- Emission can take place at a surface at zero potential as long as the electron emitted has some kinetic energy: $E_{k(Max)} > 0$
- The **Work Function** of a metal is related to the **Threshold frequency:**

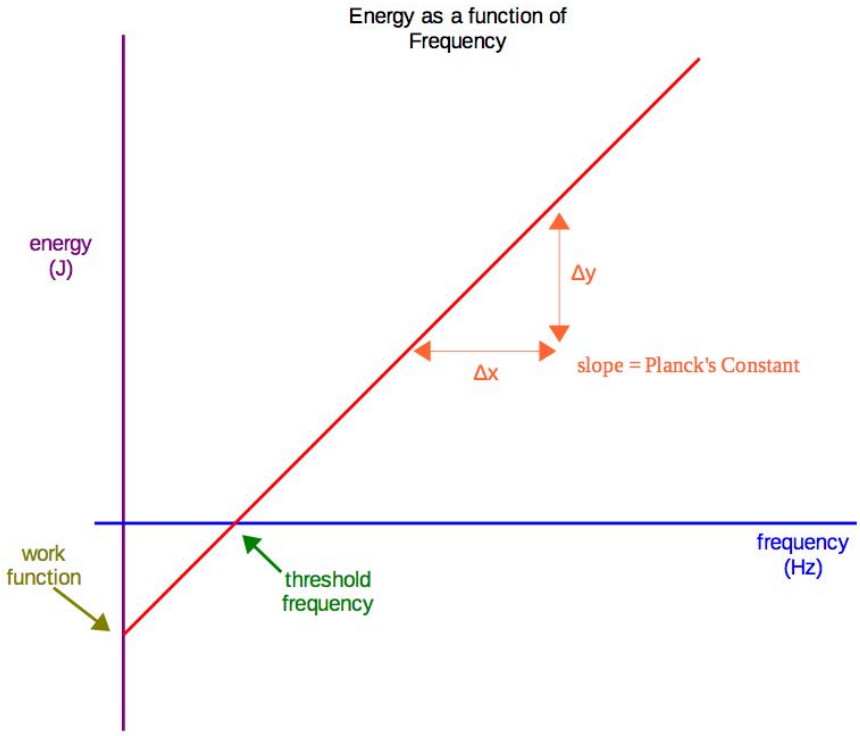
$$f_{\min} = \frac{\phi}{h}$$

where h = Planck's constant $6.63x10^{-34}$

- An emitted electron may have energy less than the maximum kinetic energy of predicted by the formula. This happens when the electron is not removed from the surface, but from deep within the metal. In order for the electron to escape from the metal, it has to work its way up to the surface, doing work and losing energy in the process. As a result, the energy it has on leaving the surface of the metal will be less than the energy it absorbed from the photon minus the work function. (remember that **one** photon hits **one** electron giving it all the energy it had)

The Photoelectric Effect Represented on a Graph

- If the maximum kinetic energies of the emitted electrons at different frequencies are known the work function and threshold frequency of that metal can be calculated by means of a graphical method:



- The vertical axis represents the maximum kinetic energy of the electron that has been emitted
    - A positive energy represents the kinetic energy of the electron emitted
    - A negative energy represents how much energy the electron (that absorbs a photon) is lacking from being able to escape the metal

- The horizontal axis represents the frequency of the light striking the metal
- We can use the graph to find several things:
    - The x-intercept of the graph represents the threshold frequency of the metal. An emitted election will have zero kinetic energy if it has just absorbed a photon of the threshold frequency.
    - The y-intercept represents the negative value of the work function of that material. Photons with zero frequency have no energy. The receiving electrons would have gained no energy and therefore would need a certain amount of energy to be emitted – this is the work function

    - Looking at the graph the gradient represents the change in energy divided by the change in frequency; that is how much the maximum kinetic energy would increase if the frequency increased by 1 Hz.

Using the equation:

$$E = hf$$

Rearranging to find h:

$$h = \frac{E}{f}$$

As $\frac{E}{f}$ *represents the gradient of the graph it can be seen that the gradient of the graph represents h – Plank's Constant!*

Collisions of Electrons with Atoms

The Electron Volt

- The electron volt is a unit of energy, and is used especially in atomic and nuclear physics where the energies that are used are very small
- **The electron volt** – is defined as the amount of energy gained by an electron as it is accelerated through a potential difference of 1 volt

$$1eV = 1.6 \times 10^{-19} J$$

Note how the electron volt is closely related to the elementary charge

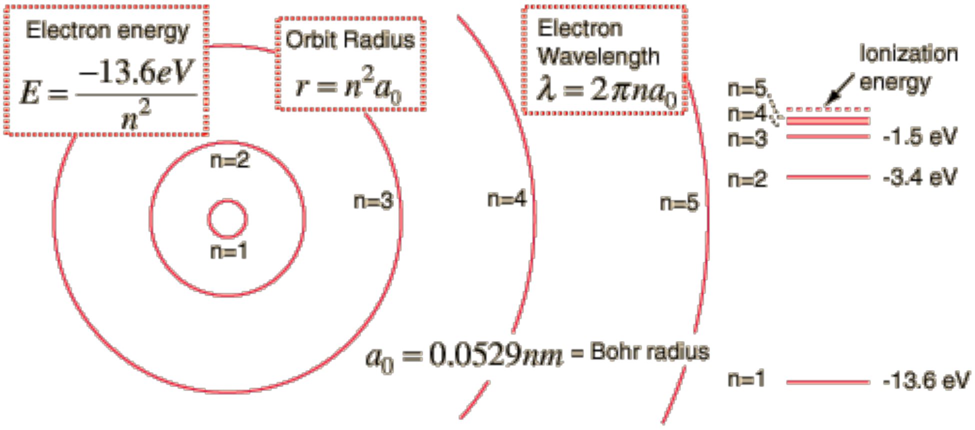
Excitation and Ionisation

- If a vaporised sample of an element has an electric current passed through it some of the electrons of the atoms of that element may absorb some energy as a result of a collision with the charge carriers passing through the vapour
- When electrons are in their lowest energy states, they are said to be in the **ground state**
- **Excitation** is when an atomic electron gains energy and as a results moves to a higher energy state (electronic orbit)
- **Ionisation** is when an atomic electron gains so much energy that it can break free of the atom and become totally dissociated from the atom
- **Ions** are charged atoms, they can be formed when electrons are removed or added
- A negative ion is formed where there are more electrons than protons
- A positive ion is formed when there are more protons than electrons

Line Spectra

- When electrons are excited by passing current though the vapour of an element, or by other means such as heating; the excited electrons do not stay in the excited state for long. They come down to lower energy states, giving off energy in the form of light.
- The light emitted can be separated into individual lines of differing wavelengths by using a diffraction grating (the angle a certain wavelength of light gets diffracted depends upon on its wavelength and follows the formula $d \sin\theta = n\lambda$ and is used in unit 2)
- This produces a **line spectra**
- The line spectra of hydrogen is shown below:

- The specific lines of the line spectra can be very useful in finding out how the electrons exist around the nucleus
- We can use these spectra lines to look at the "stationary states' of the electrons around the nucleus
- The electron quantum states and their corresponding electron energies for the hydrogen atom can be seen below:

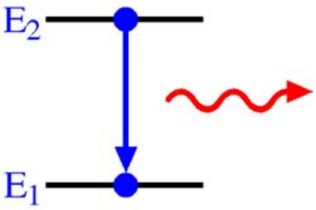


Note: the equations above are needed for the exam, however it shows that electrons in the lowest quantum state (n=1) have to gain the most energy to become free or ionised (the negative energy of each quantum state can be thought of as the energy required to free that electron from the atom or to ionises it)

- As the electrons in the atoms are excited by the electric current they gain energy, this consequently means they can occupy a higher "stationary state" or quantum level,
- This however does not last very long and very soon the electron goes back to the energy level it was excited from, as it drops down it emits a photon with energy equal to the energy it gained to get to a higher quantum state (shown in picture to the right), this emitted photon is what we see on the line spectra
-
- Therefore we can look at the different spectra lines to understand more about these different quantum states present in a atom

Photon Emission

- As stated before when an electron is excited to a higher quantum state it does not stay there long and soon moves back down emitting a photon with energy equal the energy it gained to move up the higher state
- We can therefore say the energy of the photon emitted when an electron drops from one energy level E_2 to a lower energy level E_1 follows:



$$E_{Photon} = E_2 - E_1$$

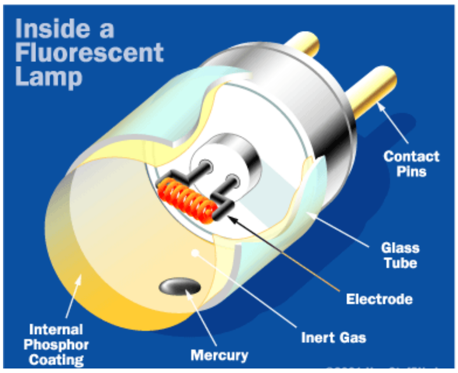
where $E_2 - E_1$ is the positive electron energy difference between the two quantum states

Florescence

- An atom in an excited state can de-excite directly or indirectly to the ground state regardless of how the excitation took place
- An atom can absorb photons of certain energies and emit photons of the same or lesser energy
- For example a electron could be excited up 2 quantum states by one photon but consequently drop to the state in-between emitting a photon and then drop again down to its ground state again emitting another photon (both of these photons would have energy less than the original photon and therefor would have a longer wavelength – this can be linked to the emission of longer wavelength visible light when certain substances are excited by Ultra-Violet light)
- This overall process explains why certain substances fluoresce or glow with visible light when they absorb UV light

Fluorescent Tube

- A fluorescent tube emits visible light when excited by means of an electric current
- Inside the tube is mercury vapour at low pressure
- The inside of the tube is coated with a fluorescent compound, typically phosphor
- A very simplified explanation of how the tube works:
    - When the tubew is switched on, the electrode heats up and emits electrons
    - Ionisation and excitation of the mercury atoms occurs as the electrons emitted collide with the mercury's atomic electrons
    - The mercury atoms emit Ultraviolet photon as well as visible photons and photons of much less energy when they de-excite
    - The ultraviolet photons are absorbed by the internal phosphor coating causing excitation of their atomic electrons
    - The atomic electrons then de-excite emitting visible photons



- Fluorescent lamps are much more efficient than filament lamps due to the fact they lose much less energy in the form of heat (a filament light bulb loses 90% of the energy supplied to heat while fluorescent only a few percent)
- Fluorescent tubes use mercury vapour at a low pressure in order to ensure the electrons gain enough energy between collisions for the collisions to result in the required excitation of the mercury atoms (in order to emit UV light), as the electrons move from one side to another they are being accelerated therefore gaining energy

Wave Particle Duality

- Light can behave as both particles and waves:
    - The wave light nature is observed thought diffraction
    - The particle like nature is observed through the photoelectric effect

Matter Waves

- If light can behave as a wave, so can other forms of matter
- Matter particles have a wave-particle nature
- The wave-like behaviour of mater is characterised by its wavelength also known as the **De Broglie Wavelength,** which is related to the momentum of the particle by the means of the equation:

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

where λ is the De Broglie wavelength of the particle, h is Plank's constant ($6.67\text{x}10^{-34}$) and p is the momentum of the particle (momentum is found by the equation: $p = mv$)

- Particles that have the **same De Broglie wavelength** have the **same momentum**!

- Particles display behaviour of both particles and waves, examples are:
    - Wave nature is shown in such experiments such as diffraction gratings
    - Particle nature is shown in photoelectric effect (atomic collisions)

Electricity

Current and Charge

- Electric current is defined as the rate at which electrically charged particles pass a point in a circuit

1 coulomb Per second = 1 Ampere

$$I = \frac{\Delta Q}{\Delta t}$$

Note: Where I is current, Q charge and T time

- The coulomb is a measure of charge
- In metallic conductors the charges particles and free electrons that travel from negative to positive (cathode to anode)
- Conventional current however and circuit diagrams regard current as traveling form positive to negative
- To make a current flow a potential difference must be present between 2 places in the circuit
- The magnitude of charge of 1 electron is $1.6 \mathrm{x} 10^{-19}$ C

Energy and Potential Difference

- **Potential Difference or voltage** is defined as the energy or work done per unit charge
- It is measured in volts, 1 volt is defined as 1 joule of energy transferred to one coulomb of charged particles

$$V = \frac{W}{Q} \text{ or } W = QV$$

Note: where v is voltage, w is the work done in moving the charged particles and q is the total charge of the charged particles

- The **emf** of a source of electricity is defined as the electrical energy produced per unit charge passing through the source. The unit of emf is the volt

Electrical Power and Current

- As $Q = I\Delta t$ (from definition of an amp) and $W = QV$ we can see that:

$$W = I\Delta tV$$

- Also because power is the rate of energy transfer (work done per unit time) or $p = \frac{\Delta E}{\Delta t}$ (where E is energy) we can see that:

$$p = \frac{I\Delta tV}{\Delta t}$$

$$p = IV$$

- Also using $V = IR$ we can sub V into $p = IV$ to give:

$$p = I^2R$$

- Using $R = \frac{V}{I}$ we can again sub into to $p = IV$ give:

$$p = \frac{V^2}{R}$$

Resistance

- **Resistance** is a measure of the difficulty of passing a current2 through a certain material, the larger the resistance the larger the voltage needed to produce a specific current in that material

$$Resistance = \frac{potential\ differance\ across\ component}{current\ passing\ through\ compounent}$$

- **Ohms law** states that the pd across a metallic conductor is proportional to the current through it provided the physical conditions do not change (temperature etc.)

$$R = \frac{V}{I}$$

$$V = IR$$

Resistivity

- Two factors that effect the resistance if a conductor are its length and its cross sectional area

$$\rho = \frac{RA}{L}$$

Where R is a given resistance value, A is the cross section area and L is the length of the wire

$$A = \frac{\pi d^2}{4} = \pi r^2$$

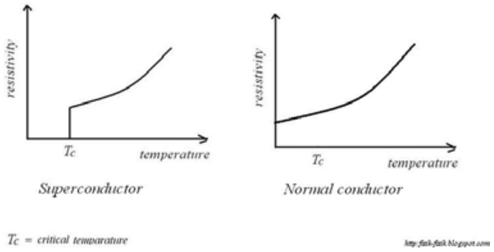
Note: When taking the diameter of the wire, take several reading and take the average to reduce inaccuracies

$$1mm = 1 \times 10^{-3} m$$

$$1mm^2 = 1 \times 10^{-6} m^2$$

Superconductivity

- A superconductive material is one that has zero resistivity when its temperature drops below a critical value (also called transition temperature)
- When a current passes through a superconductor, there is no potential difference across it as the resistance is zero
- As resistance is zero there is no energy loss
- Superconductors are used to make high-power electromagnets that generate very strong electromagnetic fields and to reduce energy loss in energy transfer through wires
- Superconductors are only really useful if the energy saved is less than the energy required to maintain the superconductor at or below the critical temperature



Temperature and Resistance in Conductors and Thermistors

- **In metallic conductors** as the temperature increases the metal's vibrating positive ions gain energy and therefor vibrate more, the result of this is that the negative charge carriers (electrons) collide more with these positive ions the more they vibrate. As the temperature increases in a metallic conductor so does the resistance

- **In thermistors** a small change in temperature results in a large change in resistance. Thermistors have a **negative temperature coefficient (NTC)** if the thermistor is an intrinsic semi-conductor such as silicon**;** as the temperature of the thermistor increases the resistance decreases. At higher temperatures the ions of the semi-conductor vibrate more and more, this would normally cause the resistance to rise however as the thermal/kinetic energy of the ions increases it is enough to release more and more charge carriers (electrons). Although collisions are more frequent the release of conduction electrons is dominant effect therefor resistance actually decreases.

Measuring Resistivity of a Conductor

Using a variable resistor

- We can vary the resistance of the variable resistor to vary the current and voltage reaching the conductor, we can use this to obtain an average resistance for a set length of the conductor (using $V = IR$)
- We can vary the length of the conductor to give us different values for resistivity and calculate an average (using $\rho = \frac{RA}{L}$)

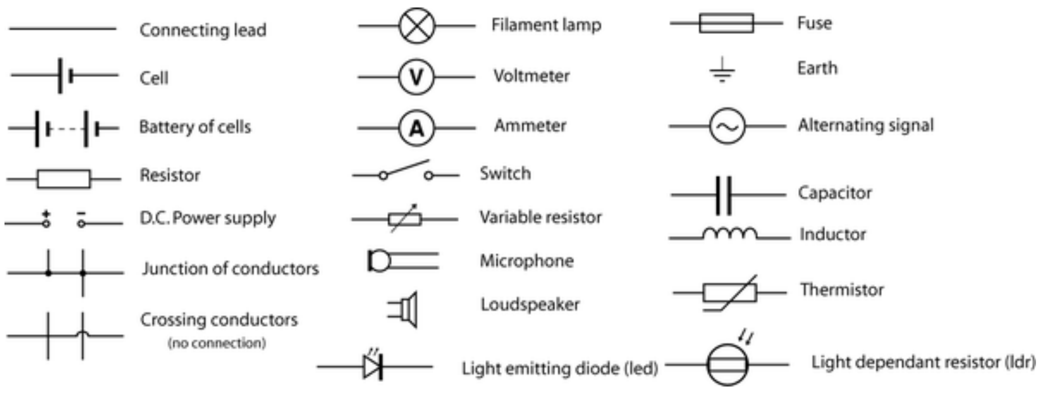
Using a Potential divider (Potentiometer)

- We can do the same as before using the potentiometer to vary the current and voltage reaching the conductor and also vary the length of the conductor
- However the benefit of using a potential divider is we can set the voltage thorough the conductor to zero while with a variable resistor we can just set it to the minimum

Components And Characteristics

- An **Ohmic component** is one that obeys ohm's law; the graph of voltage and current will be a straight line as voltage is proportional to current in an Ohmic conductor

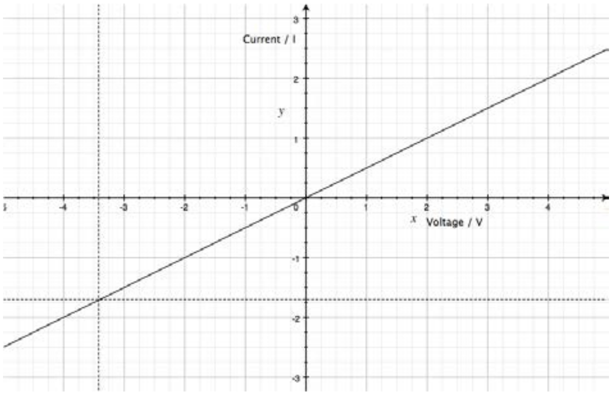
Common Components



- Both L.E.Ds and diodes have there arrows following conventional current; forward biased the arrow points from negative to positive terminals
- Thermistors have a **negative temperature coefficient (NTC)** if the thermistor is an intrinsic semi-conductor such as silicon**;** as the temperature of the thermistor increases the resistance decreases.
- The resistance of a light dependent resistor decreases with increasing light intensity
- The larger line of the cell symbol represents the positive terminal with the shorter side representing the negative end
- All symbols are used with respect to conventional current: positive to negative

Characteristics of a Wire or Resistor (Ohmic Conductor)

- Voltage always proportional to current (therefor Ohmic Conductor)



Characteristics of a Semi-Conductor Diode (Non-Ohmic Conductor)

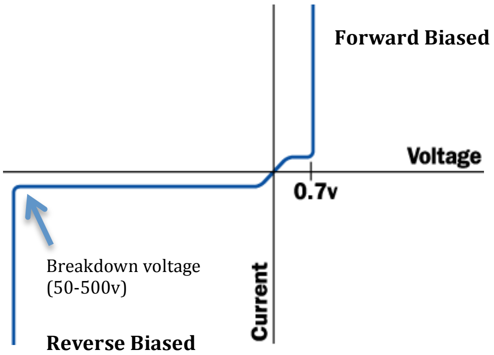
- **Semi-conductor diodes** only allowed current to flow in one direction and will only allow the current to flow above a certain voltage (typically 0.6V or 0.7V)
- The curve produced of Voltage and Current of a **semi-conductor diode** will vary depending on which way the current is sent through the diode

Forward Biased

- This is where the current flowing is in the same direction as the diode the diode is designed to allow, shown in the top right quadrant in the graph to below (conventional current flow – positive to negative)
- Between 0V and 0.7V the diode has a very high resistance and subsequently very little current flows through the diode
- Between 0.7V and 1V the resistance of the diode reduces massively and a large current is now able to flow, this is shown by a steep rise in the graph

Reverse Biased

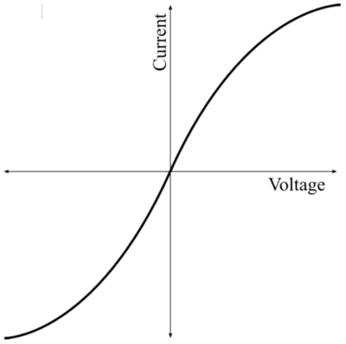
- This is where the current flowing is in the opposite direction as the diode the diode is designed to allow, shown in the bottom left quadrant of the graph above (conventional current flow – positive to negative)
- When reverse biased the diode offers high resistance hence very little current flows
- At the breakdown voltage (typically 50-500v) the diode's resistance reduces and subsequently a large current can flow however the diode is usually damaged permanently if the breakdown voltage point is reached



Note: Axes of graph are out of proportion (for exam breakdown voltage is not needed to be shown)

Characteristics of a Filament Lamp (Non-Ohmic Conductor)

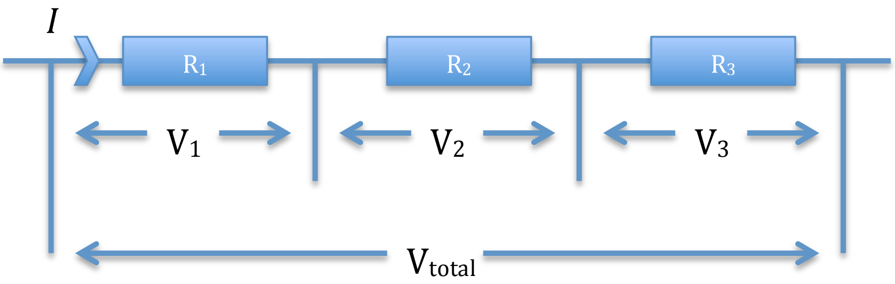
- Initially obeys ohms law as voltage/current is a straight line showing proportionality however becomes less and less steep as current increases
- This occurs because as the current increases the energy transfer to the filament increases causing the filament to heat up, this subsequently causes the resistance to increases
- As $V = IR$ if the resistance increases more and more voltage is required to increase the current hence the curve become less steep
- Filament bulbs more likely to fail when first turned on as the current is greatest initially (low resistance which increases with temp) therefore the heating effect is largest initially therefor filament more likely to melt initially



Circuit Rules

Series Resistor Circuits

- In series the same current flows thorough all components due to conservation of charge



- We can therefor generalise that in series circuits:

$$V_{total} = V_1 + V_2 + V_3 + ... + V_n$$

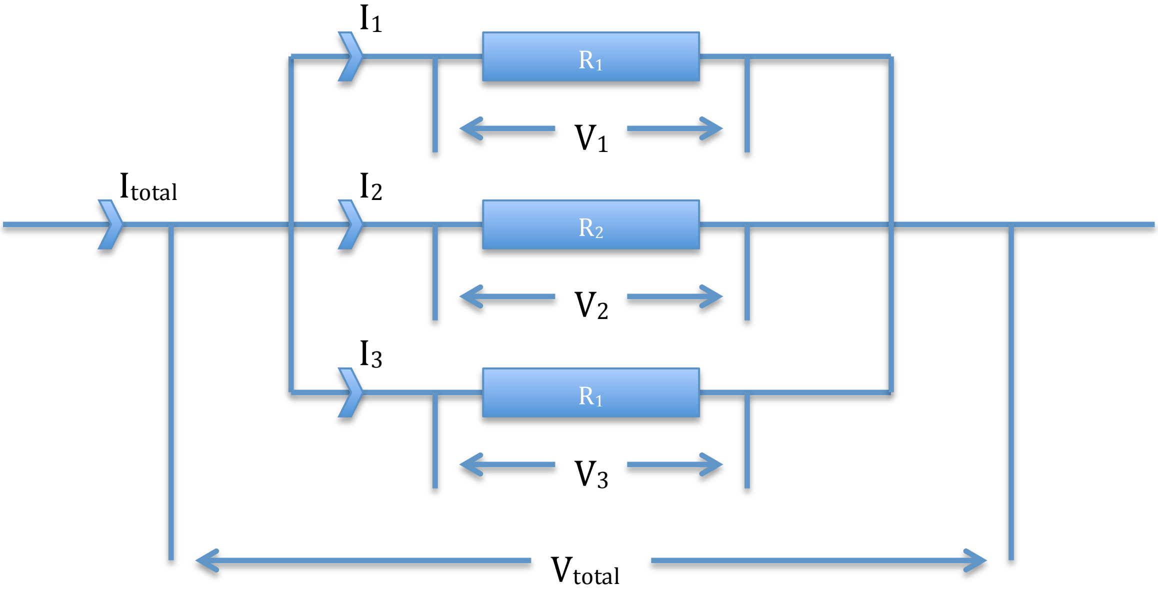
Subbing into the equation $V = IR$ *(I is also constant due to conservation of charge) :*

$$R_{total} = R_1 + R_2 + R_3 + ... + R_n$$

In series: Same Current through all components, different potential difference across individual components

Parallel Resistor Circuits

- In parallel circuits each component has the same potential difference



- We can also generalise for resistors in series:

$$I_{total} = I_1 + I_2 + I_3 + ... + I_n$$

Subbing into the equation $I = \frac{V}{R}$ *(V is also constant):*

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ... + \frac{1}{R_n}$$

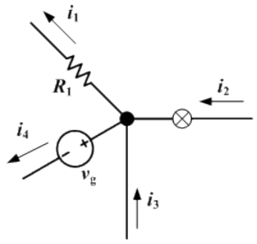
In parallel: Same potential difference through the "branches", different current through each "branch"

Kirchhoff’s Circuit Laws

Kirchhoff’s Current Law

- States that the algebraic sum of currents flowing into a junction is equal to zero
- Current flowing into a junction is regarded as positive while current travelling away is regarded as negative

$$\sum I = 0$$



Using Kirchoff’s First law we can see:
$i_1 + i_4 = i_2 + i_3$ or $0 = i_2 + i_3 + (-i_1) + (-i_4)$

Kirchhoff’s Voltage Law

- In any closed loop the algebraic sum of the *emf (electromotive force)* is equal to algebraic sum of the potential drops (voltage drops) in that loop. As the voltage can by found by the product of Current and Resistance:

$$\sum \varepsilon = \sum V$$

Note: where ε is emf and V is the voltage drop

- Care should be taken when summing the Emf as if cells are connected the wrong way round to other cells there emf works against other cells and therefor that’s cells emf is negative

EMF/Electromotive Force and Internal Resistance

- Internal resistance of a source of electricity is its opposition to the flow of charge

$$\varepsilon = \frac{W}{Q}$$

- ε is the symbol for emf and it is defined as the amount of energy the cell can provide per unit of charge
- Terminal Pd is defined as the electrical energy per unit charge that can be delivered to the external components
- If there is non-negligible internal resistance of a cell then:

$$V_{terminal} < \varepsilon$$

- “Lost Pd” is talked about as the potential difference across the "internal resistor” hence as $I = \frac{V}{I}$

$$I = \frac{\varepsilon}{R + r}$$

$$\varepsilon = I(R + r)$$

Note: where ε *is the emf, R is the total external resistance and r is the internal resistance*

Power and EMF

- The power supplied to the external components is equal to the power provided by the cell minus the power lost to internal resistance
- Using $p = I^2R$ and $I = \dfrac{\varepsilon}{R+r}$:

$$P = \frac{\varepsilon^2}{(R+r)^2}R$$

- Although not needed in specification it can be seen that **maximum power is transferred to the "load"(external components) when the load/external resistance is equal to the internal resistance**

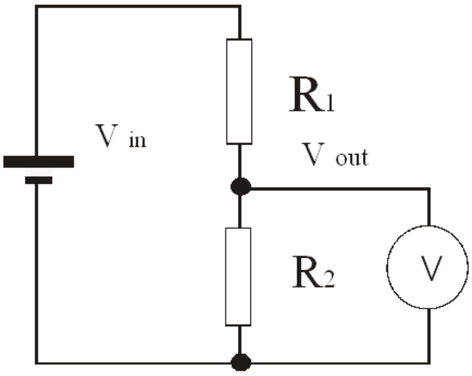
Cells in Series

- If the 2 cells are connected the same way (positive to negative): $\varepsilon_t = \varepsilon_1 + \varepsilon_2$
- If the 2 cells are connected opposite way (positive to positive): $\varepsilon_t = \varepsilon_1 - \varepsilon_2$

Cells in Parallel

- Circuit with *n* identical cells in parallel the current through each cell: $i = \dfrac{I}{n}$
- "Lost pd" in each cell or branch using $V = IR$: $v = \dfrac{I}{n}r$
- Hence each cell can provide: $V = \varepsilon - \dfrac{I}{n}r$
- Remember voltage in parallel to each branch is equal

Potential Dividers/Potentiometers



- 2 or more resistors in series with a source of a fixed potential difference (Voltage in). This fixed pd is divided between the 2 (or more) resistors and a wire can be placed in between 2 of the terminals of the resistors to create a parallel branch with varying potential (depending upon the terminals that have been connected)
- The potential divider has many uses:
  - Supply a pd between 0 and the source pd (voltage in) to a component
  - Supply a variable pd to a component
  - Supple variable pd depending upon physical conditions
- We can calculate the voltage out of a 2 resistor based potential divider as follows:

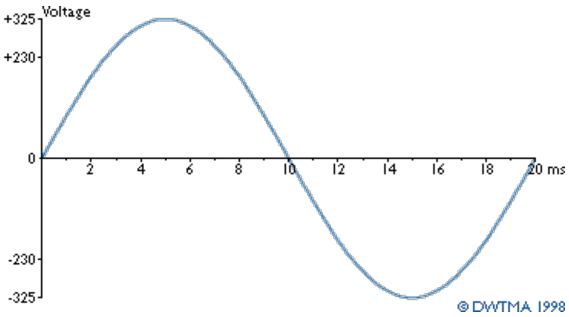
$$V_1 = V_{in}\frac{R_1}{R_1 + R_2}$$

Note: where V1 is the voltage out if we connected the "branch" to the terminals of the first resistor in the potential divider

- Notice that the equation is based upon the ratios of the parallel section's resistance compared to the total resistance of the potential divider
- Should be noted that this is not a perfect formula as adding a component to the circuit will alter the total resistance of the external compounds and thus the current flowing through the circuit at any given time

Alternating Currents

- An **Alternating current** is a current that repeatedly reverses its direction
- The **frequency** of an alternating current is the number of cycles it completes per second
- The **peak Value** of an alternating current is the maximum current or voltage which is the same in either direction (as maximum current occurs with maximum voltage)



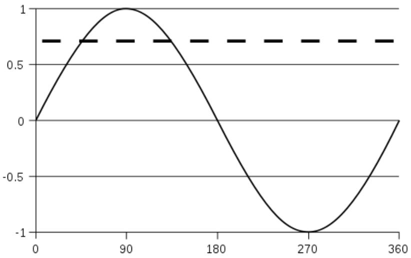
Heating Effect of an Alternating Current

- If an alternating current of a low frequency is applied through a heating element the heater would gradually heat up then cool down then heat up again then cool down again and so on and so on
- The heating effect of the current can be described as the power transferred to the heating element which can be found using the following formula:

$$p = I^2 R$$

Note: Where p is the power, I is the current through the heater and R is the resistance of the heater

- Notice though as we are using an alternating current that:
    - At peak current the power supplied is equal to $I_0^2 R$ (where I_0 is the peak current)
    - At zero current the power is zero
- For a sinusoidal current the average power over a full cycle is half the peak power
- The direct current that would give the same power as an alternating current is known as the **root mean squared value** of the current



- **Root mean squared value** of an alternating current is the value of a direct current that would give the same heating effect as the alternating current in the same resistor

Therefor:

$$I_{rms}^2 R = \frac{1}{2} I_0^2 R$$

Cancelling R:

$$I_{rms}^2 = \frac{1}{2} I_0^2$$

Square-rooting each side

$$I_{rms} = \frac{1}{\sqrt{2}} I_0$$

The same can be said for voltage (this varies the same as current)

$$V_{rms} = \frac{1}{\sqrt{2}} V_0$$

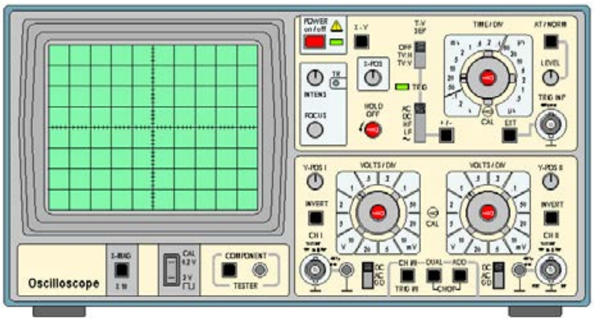
- Mains current is alternating and operates at a RMS Voltage of 230V and a frequency of 50Hz while countries such as the USA operate at 120V 60Hz

Using an Oscilloscope

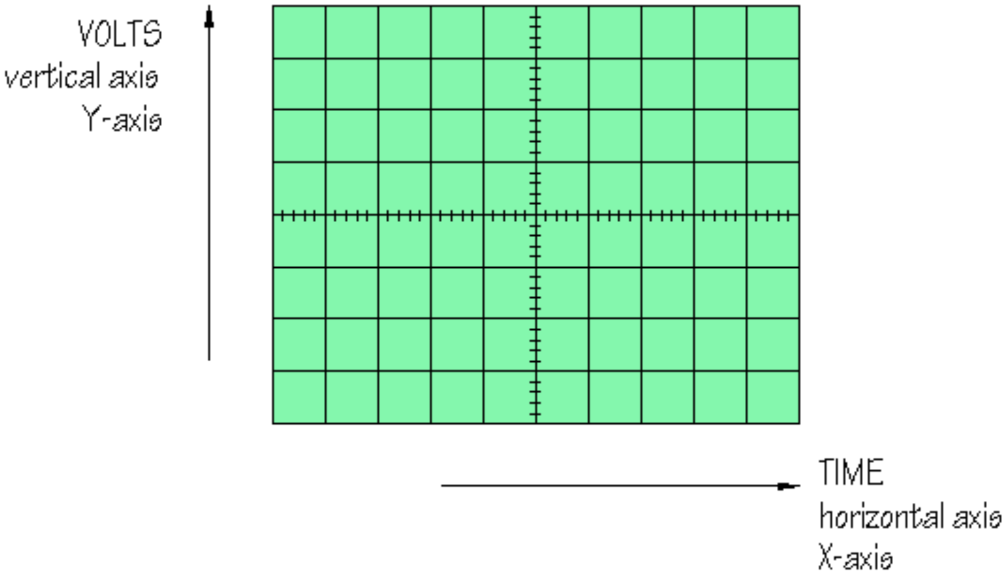
- An oscilloscope is a specifically made electron tube and associated control circuits

Reading an Oscilloscope

- A common oscilloscope can be seen to the below:



- An oscilloscope's display draws a graph of voltage against time of a specific input's signal
- On the horizontal axis is time
- On the vertical axis is voltage



- The Y-sensitivity is a setting the user can alter in order to change what each "square" of division represents vertically in terms of voltage; for example if the y-sensitivity was set to 4, this would mean every division vertically would represent 4 volts
- The x-sensitivity or "time base" is another setting the user can change to alter what each division horizontally represents in terms of time, for example a time base of 2 would mean each division horizontally represents 2 seconds