2.1 Particles

2.1.1 Atomic Model

Subatomic Particle	Charge (relative)	Charge (Coulombs)	Mass (relative)	Mass (kg)
Neutron	0	0	1	1.67×10^{-27}
Proton	+1	$+1.6 \times 10^{-19}$	1	1.67×10^{-27}
Electron	-1	-1.6×10^{-19}	$\frac{1}{2000}$	9.11×10^{-31}

Neutrons and protons are found in the nucleus (positively charged). Electrons are found around the nucleus at different energy levels.

2.1.2 Specific Charge, Proton & Neutron Numbers

Specific charge is the charge per unit mass of a particle.

$$Specific\ charge = \frac{charge}{mass}$$

Example: Sodium Nucleus

$${}^{23}_{11}Na$$

This sodium isotope has 11 protons and 12 neutrons. Each proton has a charge of 1.6×10^{-19} and both protons and neutrons have a mass of 1.67×10^{-27}. Putting this into the equation for specific charge gives:

$$Specific\ charge = \frac{11(1.6 \times 10^{-19})}{23(1.67 \times 10^{-27})}$$

Which gives a specific charge of $4.6 \times 10^{7}\ Ckg^{-1}$.

2.1.3 Isotopes

Isotopes are atoms of the same element but with different nucleon numbers (different number of neutrons).

A nuclide refers to a specific nucleus that contains a certain number of protons and neutrons. A carbon-6 nuclide and a carbon-7 nuclide are different but they are both isotopes of carbon.

Carbon Dating

All living organisms have the same amount of carbon-14 atoms as a percentage of all carbon isotopes. Once an organism dies, it no longer absorbs carbon from the atmosphere.

Carbon-14 is radioactive and will decay over a known half-life, so the older a fossil is, the fewer carbon-14 isotopes it will contain and the less radiation it will emit.

2.1.4 Stable & Unstable Nuclei

The nucleus of an atom is positively charged as the protons are positively charged and the neutrons have no charge. This means that the electromagnetic force is repelling the protons from each other, but since nuclei don't always break apart, there must be some force keeping them together (the strong nuclear force).

The Strong Nuclear force is only significant over a very short distance, roughly $1.5fm$ or $1.5 \times 10^{-15}m$. It is too weak to over come the electrostatic repulsion at distances of around $3fm$. At very close distance the Strong Nuclear force is repulsive - distances smaller than $0.5fm$. Protons and neutrons both "feel" the Strong Nuclear force.

Unstable Nuclei

α Decay

- Happens in very large nuclei.
- An α particle (^4_2He) is released.
- The proton number of the atom decreases by 2 and the nucleon number decreases by 4.

β^- Decay

- Happens in nuclei with too many neutrons.
- A neutron decays into a proton, β^- particle (electron) and an antineutrino.

$$n \rightarrow p + \beta^- + \overline{v}_e$$

- The proton number increases by 1 and the nucleon number remains the same.

β^+ Decay

- Happens in nuclei with too many protons.
- A proton decays into a neutron, a β^+ particle (positron) and a neutrino.

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

- The proton number decreases by 1 and the nucleon number remains the same.

Energy Conservation and antineutrinos When scientists first observed β^- decay, they thought that neutrons were decaying into only a proton and electron. They noticed that the energy of the neutron before the decay was larger than the energy of the proton and electron after the decay - energy was not being conserved.

To account for this, scientists hypothesised that a new type of particle was being produced and carrying away the missing energy. This particle must have a *very* small mass and no charge - so that charge was conserved.

This particle was called a neutrino, but we now know that it is an antiparticle (so an antineutrino).

2.1.5 Particles, Antiparticles & Photons

Antimatter

Antimatter is made of antiparticles. Every particle has an antiparticle. Antiparticles have the same mass and rest energy but opposite charges. They are usually labelled with a line over the top of their symbol.

Examples

Particle	Antiparticle
Proton - p (uud)	Antiproton - $\overline{p}$ $(\overline{u}\overline{u}\overline{d})$
Neutron - n (udd)	Antineutron - $\overline{n}$ $(\overline{u}\overline{d}\overline{d})$
Electron - e^-	Positron - e^+

Photon Model of Electromagnetic Radiation

Electromagnetic radiation can be thought of as little packets (photons) of energy.

Energy and Frequency The energy of a photon is directly proportional to the frequency of the wave.

$$E = hf$$

Where E is the energy of the photon, h is Planck's constant, and f is the frequency of the wave.

Annihilation and Pair Production

$$E = mc^2$$

Very famous equation, shows mass and energy are interchangeable.

Annihilation When a particle and its corresponding antiparticle collide they annihilate each other, their masses are converted into pure energy producing a pair of high-energy gamma photons. The energy carried away by each gamma photon must be at least the rest mass of one particle.

Pair Production Pair production is the opposite of annihilation. It is when one high-energy photon spontaneously turns into a particle-antiparticle pair. The energy of the photon must be at least the total rest mass energy of the particle-antiparticle pair it creates.

2.1.6 Particle Interactions

Four Fundamental Forces

Electromagnetic force

- Only acts on particles with charge
- Very strong and large range

Weak Nuclear force

- Affects all types of particles
- Responsible for β^- and β^+ decay and electron capture.
- Very weak and very short range

Strong Nuclear force

- Strongest of the four
- Very short range ($< 3fm$)
- Only experience by hadrons (particles made of quarks)
- Attractive above $0.5fm$ but repulsive below it

Gravity

- Weakest of the four
- Effects are only noticeable for huge masses (stars and planets)
- Always attractive
- Affects all matter

Exchange Particles

- Gluon - Strong Nuclear
- Photon - Electromagnetic
- $W^{\pm}/Z$ - Weak Nuclear
- Graviton - Gravity

Feynman Diagrams

(without the actual diagrams, i dont know how to get images to work on this)

General Rules

- Particles start at the bottom and move upwards
- Particles have straight lines, exchange particles have wiggly lines
- Hadrons on the left, leptons on the right
- Particles cannot cross paths, only interact via exchange particles
- A W^+ travelling from left to right is the same as a W^- travelling from right to left.

Examples (described because no images)

Electromagnetic repulsion - two electrons come close to each other and then are repelled by a virtual photon.

β^- **decay -** A neutron decays into a proton, electron and antineutrino ($n \to p + \beta^- + \overline{v}_e$). The exchange particle is W^- going from the neutron to the electron.

β^+ **decay -** A proton decays into a neutron, positron and a neutrino ($p \to n + \beta^+ + v_e$). The exchange particle is W^+ going from the proton to the positron.

Electron capture - A proton and electron interact and form a neutron and neutrino ($p + e^- \to n + v_e$). Shown as either a W^+ going from the proton to the electron or a W^- going from the electron to the proton.

2.1.7 Classification of Particles

Hadrons

- Made of quarks
- Are not fundamental

Baryons

- Contain 3 quarks or antiquarks
- Protons (uud) and neutrons (udd) are both baryons

Mesons

- Quark-antiquark pair

Pions

- Strangeness of 0
- π^+ ($u\overline{d}$)
- π^0 ($u\overline{u}$ or $d\overline{d}$)
- π^- ($d\overline{u}$)

Kaons

- Have a strangeness (1 or -1)
- K^+ ($u\overline{s}$) has a strangeness of 1
- K^0 ($d\overline{s}$ which has a strangeness of 1 or $s\overline{d}$ which has a strangeness of -1)
- K^- ($s\overline{u}$) has a strangeness of -1

Leptons

- Fundamental and cannot be broken down any further
- Electrons (e^-)
- Muon (μ^-)
- Neutrinos (v_e, v_μ)

2.1.8 Quarks and Antiquarks

Name	Symbol	Charge	Baryon no.	Strangeness
Up	u	$\frac{2}{3}$	$\frac{1}{3}$	0
Down	d	$-\frac{1}{3}$	$\frac{1}{3}$	0
Strange	s	$-\frac{1}{3}$	$\frac{1}{3}$	-1
Anti-up	$\overline{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
Anti-down	$\overline{d}$	$\frac{1}{3}$	$-\frac{1}{3}$	0
Anti-strange	$\overline{s}$	$\frac{1}{3}$	$-\frac{1}{3}$	1

2.1.9 Conservation Laws

- Charge is **always*** conserved
- Baryon number is ***always*** conserved
- Energy is ***always*** conserved
- Lepton number is ***always*** conserved but separately (both the muon lepton number and the electron lepton number)
- Strangeness is conserved for interactions with the strong nuclear force, but not always for interactions with the weak nuclear force.
- Momentum is ***always*** conserved

2.2 Electromagnetic Radiation and Quantum Phenomena

2.2.1 & 2.2.2 Photoelectric Effect

When photons with enough energy hit a metal plate, electrons can be emitted. Electrons are only emitted if the photons have a certain amount of energy (called the work function, ϕ) and since energy and frequency are linked with $E = hf$ they must also have a certain frequency (called the threshold frequency). This work function and threshold frequency is different for different types of metal but is usually in the UV range.

When the photons' frequency is above the threshold frequency, then the intensity is directly proportional to the number of electrons.

Any energy above the work function of the metal will be transferred into kinetic energy for the electrons.

$$hf = \phi + E_{k(max)}$$

Where h is Planck's Constant, f is the frequency of the photon, ϕ is the work function, $E_{k(max)}$ is the maximum kinetic energy of an electron.

As electrons are charged, when emitted they do work to move through an electric potential. The electrons will stop if all their kinetic energy is used up doing work against the potential.

The equation for the stopping potential is:

$$eV_s = E_{k(max)}$$

Where e is the charge of an electron, V_s is the stopping potential and $E_{k(max)}$ is the maximum kinetic energy.

2.2.3 Collisions of Electrons with Atoms

Ionisation

- Ionisation is when an atom has an electron removed or added, making it an ion.
- The energy needed for an electron to go from the ground state to being completely removed is called the ionisation energy.

Excitation

- Excitation is when an electron gains energy and moves up an energy level or multiple energy levels. To do this, the electron needs exactly the energy difference between the energy levels.

- Electrons can absorb energy from photons and become “excited” (this process is excitation). When moving down energy levels they release photons of equal energy that they absorbed.

Electron Volt

- An electron volt is defined as the energy given to a fundamental charge (e) accelerated through a potential difference of 1 Volt.
- $1eV = 1.6 \times 10^{-19} J$

2.2.4 Energy Levels & Photon Emission

Energy Levels

- Electrons do not float randomly around the nuclei of atoms, they are found at set energy levels and each level is given a “quantum number”, n. The ground state is the state of lowest energy and has quantum number n = 1.
- The movement of electrons between energy levels can be represented with the equation:

$$\Delta E = E_2 - E_1 = hf$$

This shows that the change in energy between the two energy levels is equal to the energy of the photon that collided with it.

Absorption Spectra

Electrons can only move between discrete energy levels, so it can only absorb (and then emit) photons with particular frequencies (and wavelengths).

White light is a continuous spectrum and contains all colours in the visible spectrum.

A cool gas (a gas containing atoms in their ground state) will absorb some frequencies of light when white light is shown through it, when the light leaving the cool gas is split by a prism black lines can be seen which correspond to the frequencies absorbed by the gas. This is the absorption spectra.

An excited gas contains atoms in an excited state, and as these electrons de-excite and fall down to lower energy levels, photons are emitted which match the black lines missing from the absorption spectra. This is the emission spectra.

The absorption and emission spectra are different for different gases.

3.2 Refraction, Diffraction and Interference

3.2.3 Refraction at a plane surface

When light changes mediums, its speed changes.

Snell's Law

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

Where n_1 and n_2 are the refractive indexes of the materials.

Critical angle

$$sin\theta_c = \frac{n_2}{n_1}$$

Where n_2 is the less optically dense material and n_1 is the more optically dense material.

The critical angle is the angle at which the light will be entirely reflected (along the boundary of the materials).

Total internal reflection is occurs at angles larger than the critical angle and no light is refracted, all of it is reflected off the boundary and does not change medium.

Fibre Optics

Optical fibres transmit light by total internal reflection.

Each fibre is made from an optically dense core and covered by cladding with very small optical density. This results in a very small critical angle which minimises the amount of light that crosses the boundary between the materials and is not transmitted.

Pulse Broadening and Absorption Material dispersion is due to different wavelengths of light arriving at the end of a fibre at different times. This is because the refractive index of the fibre changes with the frequency of light. This causes pulse broadening. To counteract this, monochromatic light can be used.

Modal dispersion is due to different paths being take by the light in the optical fibre. This means they arrive at different times at the end, which causes pulse broadening. To counteract this, a monomodal fibre can be used (very thin so different paths have a smaller effect).

As the light travels, small amounts may be absorbed by the materials, this is pulse absorption.

Both pulse broadening and absorption can be counteracted by repeaters along the optical fibre which boost the signal.

4.1 Force, Energy & Momentum

(most of the topic isn't in here because, A) its very simple, B) its done in mechanics in maths or B) i cant be bothered to include everything anymore)

4.1.11(?) Newton's Laws

Newton's 1st Law

The velocity of an object will only change if a resultant force is acting on an object.

Newton's 2nd Law

$$F = ma$$

Newton's 3rd Law

Whenever 2 objects interact, the forces they exert on each other are equal and opposite (if neither of them move).

4.1.12 Momentum

$$Impulse = \Delta p$$

Where p is momentum (mv).

Also:

$$Impulse = Force \times time$$

So:

$$\Delta p = Ft$$

Collisions

Elastic Collisions

- Momentum is conserved
- Kinetic energy is conserved

Inelastic Collisions

- Momentum is conserved
- Kinetic energy is not conserved

4.1.13 Work & Energy

$$Work\ done = force \times distance$$

The area under a force-displacement graph is the work done.

4.1.14 Power & Efficiency

Power is the rate of energy transfer (energy transferred per second).

$$Power = \frac{Work\ done}{time}$$

Power is measured in Watts (W), 1 Watt is defined as 1 Joule transferred per second.

Since $WD = Ft$, the equation for power can be written as:

$$P = Fv$$

Where P is power, F is force and v is velocity.

Efficiency

$$Efficiency = \frac{useful\ output\ power}{input\ power}$$

To find the efficiency as a percentage, just multiply it by 100.

4.2 Materials

4.2.1 Density

Density is a measure of the mass per unit volume of an object.

$$\rho = \frac{m}{V}$$

Where ρ is the density, m is the mass and V is the volume.

The most common unit of density is kgm^{-3}

4.2.2 Bulk Properties of Solids

Hooke's Law

Hooke's Law states that the force applied on an extensible object is proportional to tis extension:

$$F \propto \Delta l$$

Where F is the force, and l is the length.

The equation is more useful when shown as:

$$F = k\Delta l$$

Where k is the constant of proportionality (also known as the spring constant).

Hooke's Law only applies until the limit of proportionality. Before then a force-extension graph is linear.

The elastic limit is the maximum force an elastic object can sustain before they are unable to return to their normal position (zero extension).

4.2.3 Energy in Materials

Elastic Potential Energy

The elastic potential energy of a spring is:

$$E_e = \frac{1}{2}F\Delta l$$

Where E_e is the elastic potential energy, F is the force applied and Δl is the extension. This is just the area under a force-extension graph before the limit of proportionality.

This could also be written as:

$$E_e = \frac{1}{2}k(\Delta l)^2$$

Energy Conservation

In an impact (such as a car crash), a lot of energy can be transferred to the passengers (not good). Vehicles are designed to redirect the energy away from the passengers and to the vehicles themselves (crumple zones, seat belts, air bags).

4.2.4 Young's Modulus

Young's Modulus (E) is a property of a material that describes how easily it can stretch and deform and is defined as the ratio of tensile stress (σ) to tensile strain (ε).

$$E = \frac{\sigma}{\varepsilon}$$

The stress is given by the equation:

$$\sigma = \frac{F}{A}$$

Where σ is the stress, F is the force applied and A is the cross-sectional area the force is applied onto. The unit is Pascals (Pa)

Strain is given by the equation:

$$\varepsilon = \frac{\Delta l}{l}$$

Which is a ratio of extension to length.

This means that the equation for Young's Modulus could be rewritten as:

$$E = \frac{Fl}{\Delta l A}$$

5.1 Current Electricity

- **Current** - the rate of flow of charge ($I = \frac{Q}{t}$)
- **Voltage/potential difference** - the work done per unit charge ($V = \frac{W}{Q}$)
- **Resistance** - a measure of how hard it is for current to flow ($R = \frac{V}{I}$)

Circuit rules

The total resistance of components in series is the sum of the resistances. The total resistance of components in parallel is the reciprocal of the sum of the reciprocal of the resistances.

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

The current in series is the same everywhere. The current into a junction is the current out of the junction.

The voltage of the cell is the sum of the voltages across the components in series. In parallel, the voltage across all branches is the same.

Resistivity

The resistivity of a material is a measure of much resistance a material provides.

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

Where ρ is the resistivity, R is the resistance, A is the cross-sectional area the current is flowing through, and l is the length the current is travelling.

Superconductors

Superconductors are materials which have zero resistivity below a critical temperature.

Used in MRI machines.

Generate magnetic fields but not heat (cool).

EMF and Internal resistance

EMF (electromotive force) is the total voltage produced by the cell.

Internal resistance is the resistance within the cell, which means that the Electromotive force is not the same as the voltage across the cell.

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

ε is the electromotive force, I is current, R is the resistance within the circuit and r is internal resistance.

6.1 Periodic Motion

6.1.1 Circular Motion

Angular speed measures how quickly an object is rotating. The unit is $rads^{-1}$. The equation to calculate it is:

$$\omega = \frac{\Delta\theta}{\Delta t}$$

Where θ is the angle in radians and t is the time.

The distance travelled along the circumference (arc length) is $l = r\theta$.

In circular motion, 1 time period is the time taken to complete a full rotation of 2π radians. If we input these values into the equation for angular speed above we get:

$$\omega = \frac{2\pi}{T}$$

and since we know $f = \frac{1}{T}$ we could also write it as:

$$\omega = 2\pi f$$

The acceleration in circular motion is always directed towards the centre of the circle (this is called centripetal acceleration).

$$a_c = \frac{\Delta v}{\Delta t}$$

This can also be written as:

$$a_c = r\omega^2$$

The equation for the centripetal force is the same as for centripetal acceleration but multiplied by mass (from $F = ma$).

$$F_c = \frac{m\Delta v}{\Delta t} = \frac{mv^2}{r} = mr\omega^2$$

Simple Harmonic Motion

SHM is any motion in which the acceleration is directed towards a fixed point AND is directly proportional to the negative of the displacement. It can be defined by the equation below:

$$a = -\omega^2 x$$

Where a is the acceleration, ω is the angular velocity and x is the displacement.

In an acceleration-displacement graph of SHM, the graph is a straight line that goes through the origin and has a negative gradient.

The maximum acceleration is given by the equation:

$$a_{max} = \omega^2 A$$

Where A is the maximum displacement (amplitude).