1 Matter and radiation

1.1 Inside the Atom

Atoms can only be imaged with electron microscopes. Although we cannot see inside atoms we know from **Rutherford's alpha-scattering investigations** that every atom contains

- A positively charged **nucleus** composed of protons and neutrons.
- **Electrons** surrounding the nucleus.

A **nucleon** is a proton or a neutron in the nucleus.

Electrons are negatively charged, they are held in the atom by the electrostatic force of attraction between them and the nucleus.

- The nucleus contains most of the mass of the atom.
- Its diameter is of the order of 0.00001 times the diameter of the atom.

	Charge/C	Relative charge	Mass/kg	Relative mass
proton	$+1.6 \times 10^{-19}$	1	1.6×10^{-27}	1
neutron	0	1	1.6×10^{-27}	1
electron	-1.6×10^{-19}	1	9.1×10^{-31}	0.0005

where relative charges and masses are relative to that of the proton.

Notice that

- The electron has a much smaller mass than the proton or neutrons.
- The proton and neutron have almost equal mass.
- The electron has equal and opposite charge to the proton, the neutron is uncharged.

An **uncharged atom** has equal number of protons and electrons. An uncharged atom gains or loses electrons to become an **ion**.

Isotopes

Every atom of a given element has the same number of protons.

- The **proton number** of an element is also called the **atomic number** Z.
- The **nucleon number** of the atom A is the total number of protons and neutrons in an atom.

The nucleon number A is sometimes called the **mass number** because it is approximately the mass of the atom in relative units, as the mass of a proton or neutron is approximately 1.

Isotopes are atoms with the same number of protons and different number of neutrons.

Each type of nucleus is called a **nuclide**, and is labelled using the **isotope notation**.

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

where X is the chemical symbol of the element. The number of neutrons is given by $A - Z$.

Specific Charge

The **specific charge** of a charge particle is defined as its charge divided by mass

$$\text{specific charge} = \frac{\text{charge}}{\text{mass}}$$

The electron has the largest specific charge of any particle.

1.2 Stable and Unstable Nuclei

We know the **strong nuclear force** exist because the nuclei of a stable isotope do not disintegrate - there must be a force holding them together. The strong nuclear force

- Overcomes the **electrostatic force of repulsion** between the protons in the nucleus.
- Keeps the protons and neutrons together.

The strong nuclear force has the same effect between any two **nucleons**.

It has a range <u>no more than 3fm</u> - about the same as the diameter of a small nucleus. In contrast of the electrostatic force's infinite range. It is an **attractive force** from 3fm to 0.5fm, and a **repulsive force** smaller than that to prevent neutrons and protons being pushed into each other.

$1\text{fm} = 10^{-15}\text{m}$

The equilibrium separation is where the **force curve** (picture it in your head) crosses the x-axis.

<u>Naturally occurring</u> radioactive isotopes release three types of radiation.

Alpha radiation α

consists of **alpha particles** ${}^{4}_{2}\alpha$ each comprise of two protons and two neutrons.

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

The product nucleus with $Z-2$ protons belongs to a different element Y.

Beta radiation β

consists of fast-moving electrons know as **beta particles** ${}^{0}_{-1}\beta$.

A neutron in the nucleus changes to a proton, a beta particle is created when the change happens and is emitted instantly, an **antineutrino** $\bar{\nu}$ is also emitted. The atomic number **increases by 1** to $Z+1$.

$${}^{A}_{Z}X \rightarrow {}_{Z+1}^{\ \ A}Y + {}^{\ 0}_{-1}\beta + \bar{\nu}$$

This type of change happens to nuclei with too many neutrons.

Gamma radiation γ

is an electromagnetic radiation emitted by an unstable nucleus.

- Passes through thick metal plates.
- Has no mass and no charge.

It is emitted by a nucleus with too much energy, following an alpha or beta emission.

Discovery of the neutrino

The energy spectrum of beta particles showed that beta particles were released with kinetic energies up to a maximum depending on the isotope, where each unstable nucleus lost a certain amount of energy in the process.

Then either

- Energy was not conserved in the change, or
- Some of it was carried away by mystery particles - called **neutrinos** and **antineutrino**.

The hypothesis was proven after 20 years, where antineutrinos were detected from their interaction with the **cadmium nuclei** in a tank of water, installed next to a nuclear reactor as a controllable source of neutrinos.

We now know billions of neutrinos from the sun pass through our bodies without interacting.

1.3 Photons

Visible light is just a small part of the spectrum of **electromagnetic waves**. Our eyes cannot detect the other parts.

In a vacuum, all electromagnetic waves travel at the speed of light $c = 3.00 \times 10^8 \text{ms}^{-1}$. Where the frequency f and wavelength λ of electromagnetic radiation is related by

$$f\lambda = c$$

where the wavelength of light λ is often expressed in nanometres ($1\text{nm} = 1 \times 10^{-9}\text{m}$). Visible light have wavelength between 400nm and 700nm.

An electromagnetic wave consists of an **electric wave** and **magnetic wave** which travel together and vibrate

- At **right angles to each other** and to the direction which they are travelling.
- **In phase with each other** - the two waves reach a peak together.

The Photon Theory of Light

Electromagnetic waves are emitted by a charged particle when it loses energy, this happens when

- A fast-moving electron is **stopped**, slowed down or changed direction.
- An **atomic electron** moves to a different shell of lower energy.

Electromagnetic waves are emitted in short bursts of waves, each burst is a packet of waves referred to as a **photon**. The **photon theory** was established to explain the **photoelectric effect** - the emission of electrons from a metal surface when light is directed at the surface.

The energy E of a photon depends on its frequency f

$$E = hf$$

where $h = 6.63 \times 10^{-34}$Js is **Planck's constant**.

Power of Laser Beam

A **laser beam** consists of photons of the same frequency. The power of a laser beam is the energy per second transferred by the photons.

$$P = nhf$$

where n is the number of photons in the beam passing a fixed point each second.

1.4 Particles and Antiparticles

Matter and antimatter particles destroy each other when they meet, releasing radiation.

In a **positron emitting tomography** (PET) scanner, a positron-emitting isotope is administered to the patient. Each positron emitted meets an electron and **annihilate** each other. Two gamma photons are produced and sensed by detectors, an image of where the positron-emitting isotopes are is built up from detector signals.

The **positron** is the antiparticle of the electron.

Positron takes place when a proton changes into a neutron in an unstable nucleus with too many protons. The positron β^+ and an uncharged neutrino ν are emitted.

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + \nu$$

There are no naturally occurring **positron-emitting isotopes**. They are manufactured by placing a stable isotope in the path of a beam of protons, some of the nuclei absorb extra protons and become unstable positron-emitters.

The Theory of Antiparticles

$E = mc^2$ shows that the mass of a particle increases the faster it travels. The mass of a particle when it is stationary - its **rest mass** m_0 corresponds to **rest energy** m_0c^2 locked up as mass. It also showed that rest energy must be included in the conservation of energy.

The existence of **antiparticles** would allow rest energy to be unlocked whenever a particle and a corresponding antiparticle meet and annihilate each other.

The theory of antiparticles predicted that for every type of particle, there is a corresponding antiparticle

- **Annihilate** the particle and itself when they meet, converting their total mass into photons.

- Has the **same rest mass** as the particle.
- Has the **opposite charge** to the particle (if charged).

The opposite process of **pair production** was also predicted - a photon with sufficient energy passing near a nucleus or an electron can suddenly change into a particle-antiparticle pair, which would then be separated from each other.

Energy of Annihilation and Pair Production

The energy of a particle is measured in **mega electron volts** (MeV). One **electron volt** (eV) is defined as the energy transferred when an electron is moved through a potential difference of 1V.

Annihilation occurs when a particle and corresponding antiparticle meet

- Their mass is converted into **radiation energy**.
- **Two photons** are produced in the process.
  - A single photon cannot ensure a total momentum of zero after the collision.

The **minimum energy** of each photon is given by

$$hf_{\min} = E_0$$

where E_0 is the rest energy of the particle.

In **pair production**, a photon creates a particle and a corresponding antiparticle, and vanishes in the process. The **minimum frequency** $f_{\min}$ of the photon to produce the particle-antiparticle pair is

$$hf_{\min} = 2E_0$$

A proton with less energy cannot create the particle-antiparticle pair.

Discovery of the Positron

A **cloud chamber** is a small transparent container containing air **saturated with vapour** and made very cold. **Ionising particles** leave a visible trail of liquid droplets when they pass through the air, allowing **cosmic rays** to be photographed.

By allowing particles to pass through a **lead plate** in the chamber and applying a **magnetic field**.

- A positive particle would be <u>deflected in the opposite direction</u> to a negative particle travelling in the same direction.
- The slower it went, the more it would bend.

where he discovered a beta particle that slowed down but <u>bent in the opposite direction</u> to all the other beta trails. He had detected a positron, the first antiparticle to be detected..

1.5 Particle Interaction

When a single force acts on an object, it changes the momentum of the object.

The **momentum** of an object is its mass multiplied by its velocity.

Two objects exert **equal and opposite forces** on each other when they interact - momentum is transferred between the objects by these forces.

The **electromagnetic force** between two charged objects is due to the exchange of **virtual photons**. They cannot be detected directly, and if intercepted, would stop the force acting. A **Feynman diagram** can be used to represent the interaction.

The Weak Nuclear Force

Beta decay cannot be caused by the electromagnetic force as the neutron is uncharged. The **weak nuclear force** changes a neutron into a proton and vice versa in beta decays. It is weaker than the strong nuclear force because it doesn't affect the weak nuclear force.

In both beta decays, an electron or positron, and a neutrino or an antineutrino is created. Neutrinos hardly interact with other particles, but there are exceptions.

- A neutrino interact with a **neutron** and change it into a proton - β^- emission.
- A antineutrino interact with a **proton** and change it into a neutron - β^+ emission.

These interactions are due to the exchange of **W posons**:

- Have a non-zero rest mass.
- Have a very short range less than 0.001fm.
- Can be positively W^+ or negatively W^- charged.

W bosons was first detected when protons and antiprotons at very high energies were made to collide and annihilate each other. At sufficiently high energies, these annihilation events produce **W bosons and protons**. The β particles from the W boson decays were detected as predicted.

If no neutrino or antineutrino is present:

- $W^- \to \beta^- + \bar{\nu}$
- $W^+ \to \beta^+ + \nu$

Electron Capture

A proton in a **proton-rich nucleus** turns into a neutron as a result of interacting through the weak interaction with an **inner-shell electron** from outside the nucleus. Where a W^+ boson changes the electron into a neutrino.

$$p \to n + W^+$$
$$e^- + W^+ \to \nu$$

The same can happen when a proton and electron collide at very high speeds.

- For an electron with sufficient energy, the overall change could occur as a W^- exchange from the electron to the proton.

The photon and W bosons are known as **force carriers** because they are exchanged when the electromagnetic force and the weak nuclear force act respectively.