revisely

Particles

Constituents of the atom

For $^{A}_{Z}X$ A = mass number (protons + neutrons), Z = number of protons

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

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

Example: A Hydrogen atom ($^{1}_{1}H$) nucleus has a charge of 1.60 x 10^{-19} C and a mass of 1.67 x 10^{-27} kg, so its specific charge is 9.58 x 10^{7} Ckg^{-1}

Stable and unstable nuclei

The **strong nuclear force** overcomes the electrostatic force of repulsion between protons in the nucleus and keeps the protons and neutrons together.

- It has a range of 3-4 femtometres (fm).
- The effect is the same between two protons, two neutrons or a neutron and a proton.
- It is an attractive force between 0.5 fm to about 3 to 4 fm, and repulsive below this.
- It has exchange particle of π.

- **Alpha radiation (α)** consists of alpha particles with two protons and two neutrons, and has the symbol $^{2}_{4}\alpha$ as it has two protons and a mass of 4.
  - The following equation represents the change when an alpha particle is emitted from a nucleus:

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

- **Beta radiation (β)** consists of fast-moving electrons, and has the symbol $^{0}_{-1}\beta$ or β^{-}
  - A β– particle is released as a result of a neutron changing into a proton
  - An antineutrino is also emitted.
  - This change can be represented with the following equation:

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

- **Gamma radiation (γ)** is electromagnetic radiation emitted by an unstable nucleus.
  - It has no mass and no charge
  - It is emitted by a nucleus which has too much energy following the emission of an alpha or beta particle

Particles and antiparticles

- The **antiparticle theory** states that every particle has a matching antiparticle that:
  - Has the same rest mass and rest energy
  - Has opposite charge
  - Annihilates the particle if the two meet (see below)
- **Pair-Production** is where a gamma ray photon produces a particle and its matching antiparticle
  - Usually an electron and positron as they have a relatively low mass
  - The minimum energy for a photon to undergo pair-production is the total rest energy of the particles produced
  - Where E_0 is rest energy of particle, $E_{min} = hf_{min} = 2E_0$
- **Annihilation** is the opposite of pair-production, occurs when a particle and matching antiparticle meet and their mass is converted back to energy.
  - A pair of gamma ray photons are produced to conserve momentum
  - Both photons need to have a minimum energy, E_{min}
  - Where E_0 is rest energy of particle, $E_{min} = hf_{min} = E_0$

Particle interactions

The **electromagnetic force** between two charged particles or objects is due to the exchange of virtual photons (γ). e.g. two protons will repel each other.

The **weak nuclear force** affects only unstable nuclei - it is responsible for

neutron → proton (β^-) and proton → neutron (β^+) decay. In both, a particle and antiparticle are created but do not correspond.

- a **neutron-neutrino** interaction changes the neutron to a proton and results in β^- emission
  - W^- boson exchange particle

$$n + V_e \rightarrow n + \beta^-$$

- a **proton-antineutrino** interaction changes the proton to a neutron and results in β^+ emission.
  - W^+ boson exchange particle

$$p + \overline{V_e} \rightarrow n + \beta^+$$

- These interactions are due to the exchange of **W bosons**. Unlike photons they have:
  - non-zero rest mass
  - very short range $\leq \frac{1}{1000}$ fm
  - positive or negative charge

If no neutrino or antineutrino is present, W^- decays to $\beta^- + \overline{V_e}$, and W^+ decays to $\beta^+ + V_e$. Note that charge is conserved.

- **β^- decay**: $n \rightarrow p + \beta^- + \overline{V_e}$

- **β^+ decay**: $p \rightarrow n + \beta^+ + V_e$

In **electron capture** a proton in a proton-rich nucleus turns into a neutron through weak force interaction with an inner-shell electron.

$$p + e^- \rightarrow n + V_e$$

The same can happen when a proton and electron collide at very high speed. For an electron with sufficient energy the overall change could occur as W^- exchange from e^- to p.

Particle classifications

Hadrons are particles/antiparticles which interact through the **strong** force - protons, neutrons, π-ons and K-ons.

Hadrons can interact through all four interactions. They interact through the strong force and electromagnetic interaction if charged. Other than the proton, which is stable, hadrons tend to decay through the weak force.

Hadrons are further divided into:

- **Baryons** - protons and all other hadrons including neutrons that decay into protons directly or otherwise
- **Mesons** - hadrons not including protons in their decay products (i.e. π and K mesons)

Leptons do not interact through the strong force - they interact only through the weak, gravitational and (if charged) electromagnetic interactions.

- **Lepton decays**:
  - $K \rightarrow \pi$ or $\mu + \overline{V_\mu}$ or $\overline{\mu} + V_\mu$
  - $\pi^\pm \rightarrow \mu + \overline{V_\mu}$ or $\overline{\mu} + V_\mu$
  - $\pi^0 \rightarrow \gamma$ (high energy photons)
  - $\mu \rightarrow e^- + \overline{V_e}$
  - $\overline{\mu} \rightarrow e^+ + V$
  - Note that decays always obey conservation rules for energy, momentum & charge.
  - Rest energy of products = total energy before – kinetic energy of products

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Leptons and quarks

Leptons and antileptons can interact to produce hadrons - this is due to the production of quarks during these events.

An up-quark has charge $+\frac{2}{3}$, and down-quark $-\frac{1}{3}$

- In a lepton-hadron interaction a neutrino or antineutrino can change into or from a corresponding charged lepton.
  - $Ve + n \rightarrow p + e^-$
  - but even though Q conserved $\overline{V_e} + n \not\rightarrow \overline{p} + e^+$
  - this is because the **lepton number** must balance

- Muon μ decay: μ changes to Ve and e^- created to conserve charge, and $\overline{V_e}$ to preserve lepton number
    - e.g. $\mu^- \rightarrow e^- + \overline{V_e} + V_\mu$
    - But $\mu^- \not\rightarrow e^- + \overline{V_e} + \overline{V_\mu}$ even though charge conserved - because lepton number is not.
    - Muon can change only into a muon neutrino (not antineutrino).
    - Electron can only be created with an electron antineutrino
- Lepton number +1 for any lepton, –1 for any antilepton, 0 for non-lepton

From smallest to greatest rest mass: e^- ...×200... μ^-, $\pi^{0/\pm}$, $K^{0/\pm}$ ... p

- $K \rightarrow \pi$, $\mu^- + \overline{V_\mu}$, or $\mu^+ + V$
- $\pi^\pm \rightarrow \mu + \overline{V_\mu}$ or $\mu^- + V_\mu$
- $\pi^0 \rightarrow \gamma$ (high energy photons)
- $\mu \rightarrow e^- + \overline{V_e}$
- $\overline{\mu} \rightarrow e^+ + V_e$

Strange particles are produced through the **strong** interaction and decay through the **weak** interaction.

- For strangeness +1, need **antistrange** quark. For strangeness –1, need strange quark.
- Mesons are hadrons which consist of two quarks - one quark and one antiquark.
    - π^0 = any $q\text{-}\overline{q}$ combination - so can be strange: $\pi^+ = u\overline{d}$, $\pi^- = \overline{u}d$
    - each pair of charged mesons is a particle-antiparticle pair
    - antiparticle of any meson is a $q\text{—}\overline{q}$ pair thus another meson.
    - hence **only K** are strange
    - $K^0 = d\overline{s}$ (+1 strange), $K^0 = \overline{d}s$ (–1 strange)
    - $K^+ = u\overline{s}$ (+1 strange), $K^- = \overline{u}s$ (–1 strange)

- Baryons are also hadrons, but consist of three quarks - all of which are antiquarks in an antibaryon:
    - proton = uud, antiproton = $\overline{u}\,\overline{u}\overline{d}$
    - neutron = udd
    - the proton is the only stable baryon — a free neutron decays into a proton, releasing an electron and antineutrino (β^- decay)
- Quarks are key to β decay
    - β^- decay - d → u quark (neutron to proton)
    - β^+ decay - u → d quark (proton to neutron)
- When balancing equations note that strangeness is **conserved** in any **strong** interaction

- but in weak interactions strangeness can change by 0, +1 or −1 (because strange particles decay in the weak interaction)