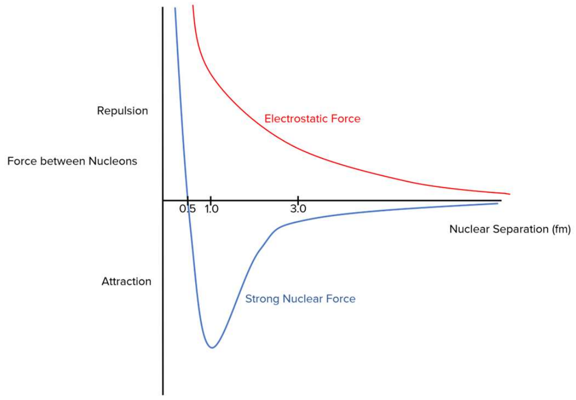
3.2.1 Particles

3.2.1.1 Constituents of the atom

- Constituents of an atom
Particle	Charge (C)	Relative charge	Mass (kg)	Relative Mass	Specific Charge (Ckg^{-1})
Proton	$+1.6 \times 10^{-19}$	+1	$1.67(3) \times 10^{-27}$	1	9.58×10^{7}
Neutron	0	0	$1.67(5) \times 10^{-27}$	1	0
Electron	-1.6×10^{-19}	-1	9.11×10^{-31}	0.0005	1.76×10^{11}
- Specific charge
  - $\text{specific charge} = \dfrac{\text{charge}}{\text{mass}}$
  - Unit = C kg^{-1}
- Nuclide notation
  - ${}^{A}_{Z}X$
  - A = nucleon / mass number = number of protons + number of neutrons
  - Z = proton / atomic number = number of protons
  - X = symbol for the element
- Isotopes
  - Atoms with the same number of protons but different numbers of neutrons
- Nuclide
  - A type of nucleus

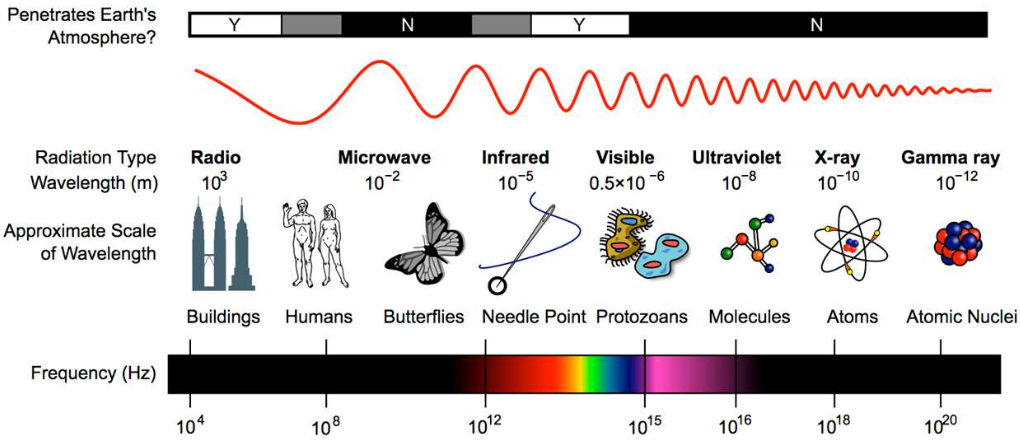
3.2.1.2 Stable and unstable nuclei

- The strong nuclear force (SNF)
  - One of the 4 fundamental forces of nature
  - Keeps the nucleus stable by counteracting the electrostatic force of repulsion between protons in the nucleus and keeping protons and neutrons together
  - Only acts on nucleons, has a very short range
    - Short-range attraction up to separation of 3 fm (1 fm = 10^{-15} m)
    - Very-short range repulsion for separations less than about 0.5 fm
    - 

- Unstable nuclei
  - Too many protons / neutrons / both
  - SNF not enough to keep them stable
  - Decay in order to become stable (type depends on the amount of each nucleon)
- Alpha decay
  - **Too many protons and neutrons**
  - Alpha particle emitted
  - ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$
- Beta-minus decay
  - **Too many neutrons** (neutron-rich)
  - A neutron changes into a proton

- Fast-moving electron (beta particle) + an antineutrino (antiparticle with no charge) emitted
- ${}^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + {}^{0}_{-1}\beta + \bar{v}$
- Neutrino ($\bar{v}$)
  - At first scientists believed that only an electron was emitted from the nucleus during beta-minus decay
  - Observation of energy levels before + after decay showed that energy was not conserved (some energy was lost)
  - Neutrinos were hypothesised for the loss of energy and later observed

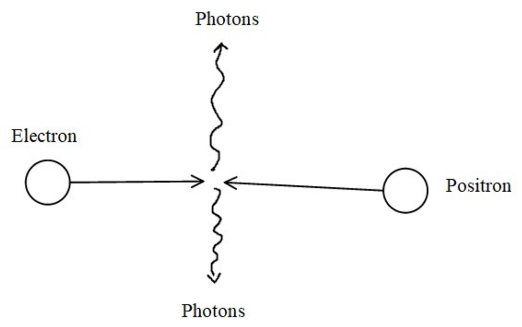
3.2.1.3 Particles, antiparticles and photons

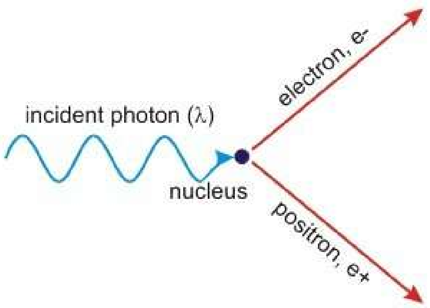
- EM waves
  - Emitted by a charged particle when it loses energy
    - When a fast-moving electron is stopped / slows down / changes direction
    - When an electron in a shell of an atom moves to a different shell of lower energy
  - 

- Photon model of EM radiation
  - EM waves are emitted as short burst of waves
  - Each burst = a packet of EM waves = a proton
  - Photons transfer energy and have <u>no mass</u>
  - The energy of photons is directly proportional to the frequency of EM radiation
    - $E = hf = \frac{hc}{\lambda}$
    - h = Planck constant = 6.63×10^{-34} Js
- Rest energy
  - Unit = MeV (millions of electron volts) = 1.60×10^{-13} J
  - 1 electron volt = the energy transferred when an electron is moved through a p.d. of 1 V
  - 1 eV = 1.60×10^{-19} J
- Antiparticle
  - Same rest energy and mass as the particle but all other properties are opposite
  - For every type of particle there is an antiparticle
- Types of antiparticles

Particle	Antiparticle
Electron	Positron
Proton	Antiproton
Neutron	Antineutron
Neutrino	Antineutrino

- Annihilation
  - Where a particle and a corresponding antiparticle meet and their mass is converted into radiation energy
  - Two photons moving in opposite directions are produced in the process so momentum is conserved

- 

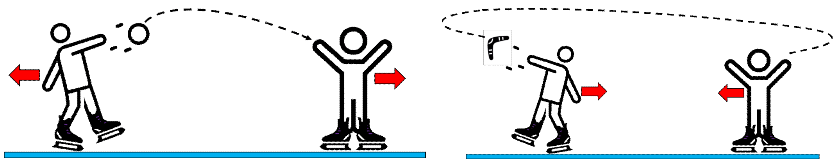
- PET scanner
    - Position emission topography
    - Allows 3D images of the inside of the body to be taken
    - Position-emitting isotope administered to patient, some reach the brain via the blood system
    - As positions are released they annihilate with electrons already in the patients system
    - Two gamma photons released for each annihilation which can be easily detected
    - Image built up gradually
- Pair production
    - A photon is converted into a particle and a corresponding antiparticle
    - Can only occur when the photon has an energy greater than the total rest energy of both particles
        - Minimum energy of a photon needed, hf_{min} = 2 × rest energy = $2E_0$
    - Excess energy = converted into KE of particles
- 

3.2.1.4 Particle interactions

- Four fundamental interactions
    - Gravity
    - Electromagnetic
    - Weak nuclear
    - Strong nuclear / strong interaction
- Exchange particles model
    - Forces between particles are caused by exchange particles (force carriers)
    - Exchange particles carry energy and momentum between the particles experiencing the force
    - Each fundamental force has its own exchange particles
        -

Interaction	Exchange particle / gauge bosons	Range (m)	Acts on	Strength
Strong nuclear	Pions (particles) Gluon (quarks)	10^{-15}	Hadrons	Strongest
Weak nuclear	W boson (W^+ or W^-)	10^{-18}	All particles	2nd weakest
EM	Virtual photon (γ)	Infinite	Charged particles	2nd strongest
Gravity	*Graviton	Infinite	Particles with mass	Weakest

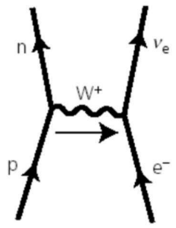
    - Momentum transferred from one particle to another

- 

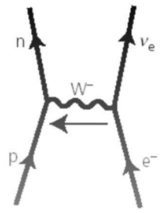
Repel Attract

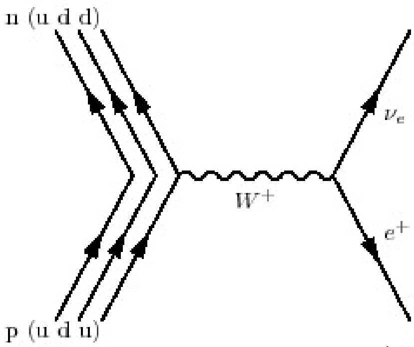
- The weak nuclear force
  - Responsible for beta decay, electron capture and electron-proton collisions
  - Exchange particles = W bosons (W^+ or W^-)
    - Non-zero rest mass
    - Very short range $\leq$ 0.001 fm
    - Positively or negatively charged
- Electron capture / electron-proton collisions
  - Same equation + different exchange particle
  - $p + e^- \rightarrow n + v_e$

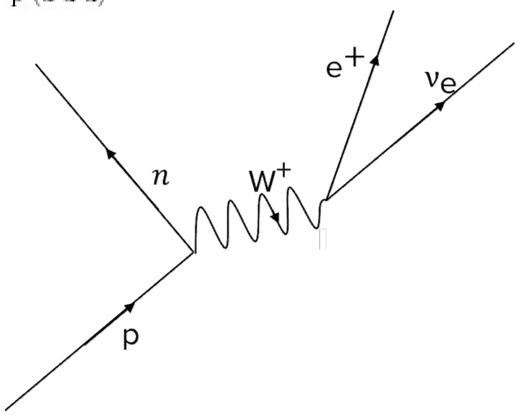
Electron capture
$p + e^- \rightarrow n + v_e$



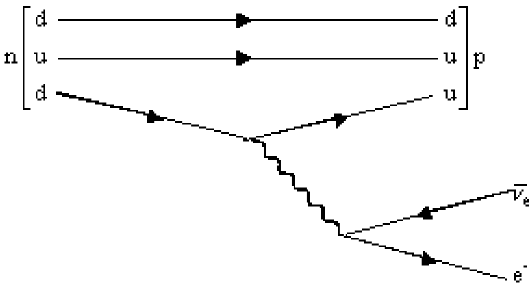
- Proton – electron collision
$p + e^- \rightarrow n + v_e$

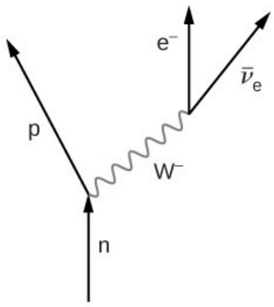


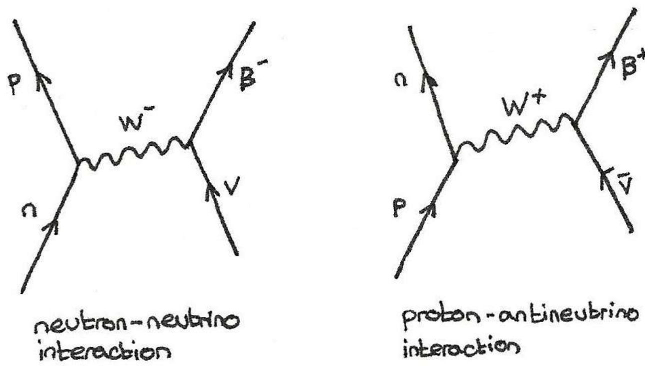
- Beta-plus / beta-minus decay
  - Beta-plus: $p \rightarrow n + e^+ + v_e$
    - 

    - 

  - Beta-minus: $n \rightarrow p + e^- + \overline{v_e}$

    - 

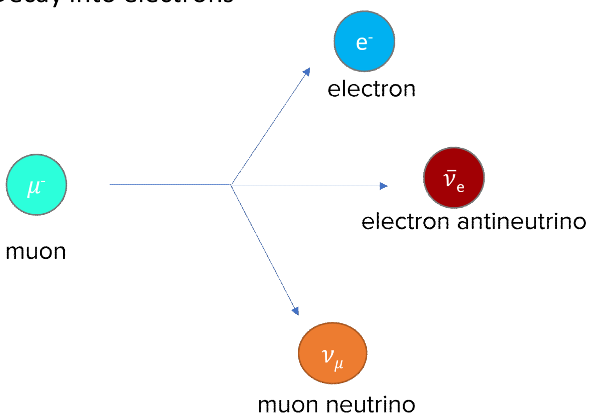
    - 

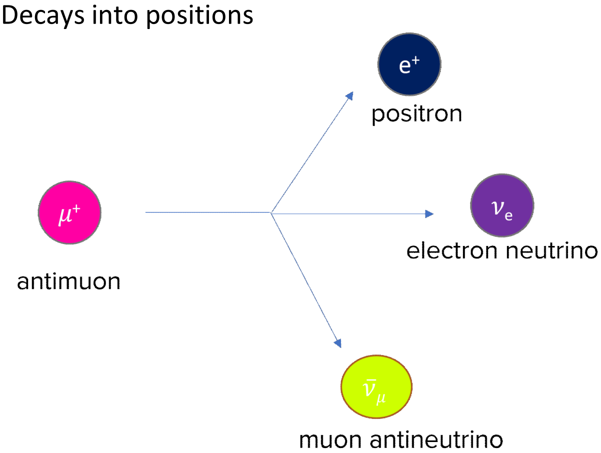
- Other W boson interactions
  - 

3.2.1.5 Classification of particles

- Classifying particles
  - All particles are either hadrons or leptons
  - Leptons = fundamental particles, cannot be broken down any further + do not experience SNF
  - Hadrons = formed of quarks (fundamental particles), experiences SNF, tend to decay through weak interaction
  - Both experience weak interaction, gravitational interaction and electromagnetic interaction (if charged)
- Types of hadrons
  - Baryons / antibaryons
    - Formed of 3 quarks / antiquarks
    - Protons and all hadrons (incl. neutrons) that <u>eventually decay into protons</u>
    - Baryons = protons, neutrons, etc., antibaryons = antiprotons, antineutrons, etc.
  - Mesons
    - Formed of 1 quark + 1 antiquark
    - Hadrons that <u>do not include protons</u> in their decay products
    - Pion / π meson
      - The lightest and most stable meson
      - Produced in high energy particle collisions, discovered in cosmic rays
      - Exchange particle for SNF
      - Different charges: π^+, π^-, π^0
    - Kaon / K meson
      - Heavier + less stable
      - Produced by the strong interaction between pions and protons
      - Eventually decay into pions (many possibilities)
      - Different charges: K^+, K^0, K^-
- Baryon number

- 1 = baryon, -1 = antibaryon, 0 = not a baryon
- A quantum number
- Always conserved in particle interactions

- Proton
  - The only stable baryon
  - All baryons will eventually decay into a proton
- Types of leptons
  - Electron
    - Stable
    - Relative charge = -1
    - Neutrino = electron neutrino
  - Muon / ų$^{-}$
    - Heavier than electrons
    - More unstable
    - Relative change = -1
    - Neutrino = muon neutrino
    - Decay into electrons
    - 

  - Neutrinos / v_e, v_u
    - Negligible mass
    - 0 charge
    - Only interact through weak interaction
    - The most abundant leptons in the universe
  - Antimuon / ų$^{+}$
    - Decays into positions
    - 

- Lepton number
  - Gives the number of leptons
  - 1 = lepton, -1 = antilepton, 0 = not a lepton
  - 2 types
    - Electron lepton number: +1 for electrons and electron neutrinos, and -1 for positrons and electron antineutrinos
    - Muon lepton number: +1 for muons and muon neutrinos, and -1 for anti-muons and muon antineutrinos
    - Both conserved during reactions

- Strangeness
    - A quantum number
    - Reflect the fact that strange particles are always created in pairs
    - Always conserved in strong interactions
    - Change by 0, +1 or -1 in weak interactions
- Strange particles
    - Particles which are produced by the strong nuclear interaction but decay by the weak interaction
    - Strange particles are created in twos
    - e.g. kaons (decay into pions through the weak interaction), assume all others are non-strange particles
- Investigating particle physics
    - Particle accelerators may be built
    - These are very expensive + produce huge amounts of data
    - Scientific investigations rely on collaboration of scientists internationally

3.2.1.6 Quarks and antiquarks

- Properties of quarks

Quark particle	Charge *Q*	Strangeness *S*	Baryon number *B*
Up u	+2/3	0	+1/3
Down d	-1/3	0	+1/3
Strange s	-1/3	-1	+1/3

- Properties of antiquarks

Antiquark particle	Charge *Q*	Strangeness *S*	Baryon number *B*
Up $\bar{u}$	-2/3	0	-1/3
Down $\bar{d}$	+1/3	0	-1/3
Strange $\bar{s}$	+1/3	+1	-1/3

- Combination of quarks and antiquarks in baryons / antibaryons

Particle	Combination	Baryon number
Proton	uud	1
Neutron	udd	1
Antiproton	$\overline{uud}$	-1
Antineutron	$\overline{udd}$	-1

- Combination of quarks and antiquarks in mesons

Particle	Combination	Charge (e)	Strangeness	Baryon number
π^0	$u\bar{u}$ or $d\bar{d}$	0	0	0
π^+	$u\bar{d}$	+1	0	0
π^-	$\bar{u}d$	-1	0	0
K^0	$d\bar{s}$ or $\bar{d}s$	0	$d\bar{s}$ = +1, $\bar{d}s$ = -1	0
K^+	$u\bar{s}$	+1	+1	0
K^-	$\bar{u}s$	-1	-1	0

- Neutron decay
    - Decay into proton as neutrons are baryons
    - A down quark changes to an up quark
    - $n \rightarrow p + e^- + \overline{\nu_e}$

3.2.1.7 Applications of conservation laws

- Properties conserved in particle interactions
    - Energy and momentum: always
        - Reactants rest energy < products rest energy = reactants KE > products KE
    - Charge: always
    - Baryon number: always
    - Electron lepton number: always
    - Muon lepton number: always
    - Strangeness: only in strong interactions
    - All conservation laws obeyed = the interaction is possible
- β decay
    - β^- decay
        - A neutron in a neutron-rich nucleus will decay into a proton
        - A down quark changes to an up quark
        - $n \rightarrow p + e^- + \overline{v_e}$
    - β^+ decay
        - A proton in a proton-rich nucleus changes into a neutron
        - An up quark changes to a down quark
        - $p \rightarrow n + e^+ + v_e$