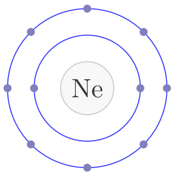
Particles and Radiation

1 Particles

1.1 Constituents of the Atom

1.1.1 The Atom



Atoms are particles consisting of protons, neutrons within the nucleus and electrons orbiting around the nucleus.

- Protons have a relative charge of +1.
- Neutrons have a relative charge of 0.
- Electrons have a relative charge of −1.

Electron charge is a physical constant of 1.602×10^{-19} C.

1.1.2 Atomic Mass Unit (amu)

Atomic Mass Unit is defined as one-twelve of the mass of a carbon-12 atom. $1\,\text{amu} = 1.661 \times 10^{-27}$ kg.

1.1.3 Specific Charge

Specific charge is the ratio of a particle's charge relative to its mass.

$$\text{Specific Charge} = \frac{\pm\text{Charge}}{\text{Mass}} = \frac{\pm Q}{M} \tag{1}$$

Specific charge can be positive or negative and it can measure particles, nuclei and ions.

1.1.4 Standard Atomic Notation

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

- A is the nucleon number or mass number.
- Z is the proton number or the charge.
- X is the chemical symbol of the element.

1.1.5 Isotopes

Isotopes are the same element with different number of neutrons within the nucleus, i.e., same number of proton and different number of neutron.

1.2 Stable and Unstable Nuclei

1.2.1 Strong Nuclear Force

Since the nucleus is positively charged (proton against proton) and same charges repel, a force must hold the protons and neutrons together to form a stable nucleus. This force is called the strong nuclear force.

Stable nuclei which does not have the tendency to decay is held together by the strong nuclear force. The strong nuclear force is attractive up to 3 fm while it is repulsive for distances below 0.5 fm.

The strong nuclear force keeps the nucleus, consisting of protons and neutrons, together within the distances of 3 fm and 0.5 fm.

1.2.2 Unstable Nuclei

Unstable nuclei can lead to alpha (α) or beta-minus (β^-) decays.

Alpha Decay

$${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \longrightarrow {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\mathrm{Y} + \alpha \tag{2}$$

$${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \longrightarrow {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He} \tag{3}$$

Beta Decay

$${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \longrightarrow {}_{\mathrm{Z}+1}{}^{\mathrm{A}}\mathrm{Y} + {}_{-1}^{\;0}\beta + \bar{\nu}_e \tag{4}$$

$${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \longrightarrow {}_{\mathrm{Z}+1}{}^{\mathrm{A}}\mathrm{Y} + \mathrm{e}^- + \bar{\nu}_e \tag{5}$$

1.2.3 The Existence of the Neutrino

Beta-minus decay was first theorized to only emit a beta-minus particle. When the energy released from a beta-minus decay is measured, there was a limit to the energy within the beta-minus particle. Since energy is conserved, the excess energy from the decay is then explained by a third particle being created: the neutrino.

1.3 Particles, Antiparticles and Photons

1.3.1 Particle-Antiparticle Pair

Every particle has its corresponding antiparticle. Photons are considered to be its own antiparticle.

$$\begin{gathered}\text{proton} \Leftrightarrow \text{antiproton}\\ \text{neutron} \Leftrightarrow \text{antineutron}\\ \text{electron} \Leftrightarrow \text{positron}\\ \text{photon} \Leftrightarrow \text{photon}\end{gathered}$$

Every particle has equal rest mass and rest energy as its antiparticle. Other quantities such as charge are equal in magnitude but opposite in sign.

$$\text{electron} \Rightarrow \begin{array}{l}\text{charge: } -1\text{e}\\ \text{rest energy: } 0.511\,\text{MeV}\end{array}$$

$$\text{positron} \Rightarrow \begin{array}{l}\text{charge: } +1\text{e}\\ \text{rest energy: } 0.511\,\text{MeV}\end{array}$$

Rest mass is most commonly measured with MeV (mega-electronvolt). Although MeV is a measurement of energy. Rest energy is derived from rest mass and is interchangeable (mass-energy equivalence: $E_0 = m_0 c^2$).

1.3.2 Photon Model of Electromagnetic Radiation

In the photon model, electromagnetic radiation is carried in discrete energy packets called photons. Photons itself has no mass. Energy of a photon is directly proportional to its electromagnetic frequency.

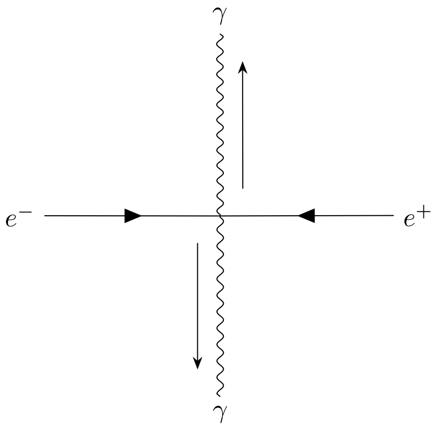
$$E = hf = \frac{hc}{\lambda} \tag{6}$$

The Planck constant, h $(= 6.63 \times 10^{-34}\,\mathrm{JHz^{-1}})$, is a physical constant that gives the relationship between the energy of a photon and its frequency.

1.3.3 Annihilation and Pair Production

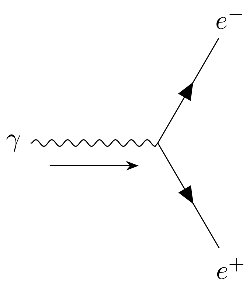
Annihilation occurs when a particle and its corresponding antiparticle pair collides to produce 2 photons from the sum of the rest energy. In annihilation, energy and momentum are conserved. Conservation of momentum is why 2 photons are created.

Electron-Positron Annihilation Diagram



Pair production occurs when a photon is converted into corresponding particle-antiparticle pair. The energy of the photon must be greater than the sum of rest energy of the particle-antiparticle pair. Excess energy is converted into kinetic energy within the particles.

Pair Production of Electron and Positron



1.4 Particle Interactions

1.4.1 Fundamental Forces

There are four fundamental forces:

1. Strong nuclear force
2. Weak nuclear force
3. Electromagnetic
4. Gravity

1.4.2 Exchange Particles

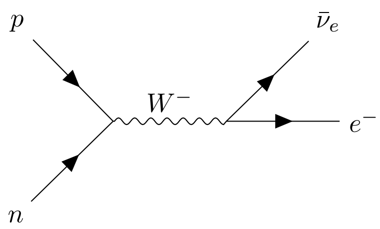
Exchange particles are force carriers where every particle interaction happens through. Exchange particles carry energy and momentum between particles that Isotopes experiencing the fundamental forces. Each fundamental force has its own force carriers.

Fundamental Force	Exchange Particles
Strong Nuclear Force	Gluons (pions, kaons, etc.)
Weak Nuclear Force	W^+, W^-, Z^0 boson
Electromagnetic Force	Virtual photon
Gravity	Graviton (theorised)

1.4.3 Boson in Weak Interactions

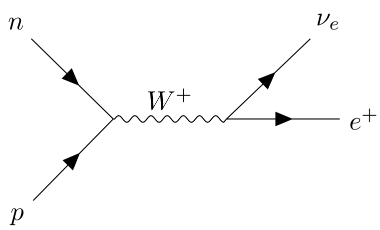
The weak nuclear force is responsible for beta decays, electron capture and electron-proton collisions. All of which utilizes W boson as the exchange particle.

β^- Decay



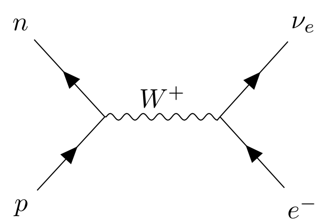
$$n \longrightarrow p + e^- + \bar{\nu}_e$$

β^+ Decay



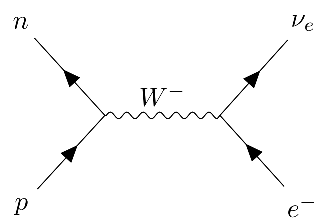
$$p \longrightarrow n + e^+ + \nu_e$$

Electron Capture



$$p + e^- \longrightarrow n + \nu_e$$

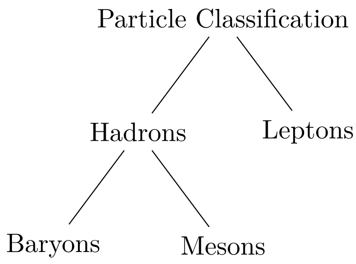
Electron-Proton Collision



$$p + e^- \longrightarrow n + \nu_e$$

1.5 Classification of Particles

All particles fall into 2 categories: hadrons and leptons. Hadrons consists of quarks while leptons are fundamental particles. Leptons cannot interact with the strong nuclear force.



Baryons consists of any combination of 3 quarks or antiquarks. Mesons consists of a quark and an antiquark.

The classes of particles also have their corresponding antiparticles.

$$\text{proton (baryon)} \Leftrightarrow \text{antiproton (antibaryon)}$$
$$\text{electron (lepton)} \Leftrightarrow \text{positron (antilepton)}$$
$$\text{pion } \pi^+ \text{ (meson)} \Leftrightarrow \text{pion } \pi^- \text{ (meson)}$$
$$\text{kaon } K^0 \text{ (meson)} \Leftrightarrow \text{kaon } \bar{K}^0 \text{ (meson)}$$

Pions are exchange particles for the strong nuclear force. Kaons decay into pions. The only stable baryon is the proton, every other baryon decays into protons.

Muon are a flavour of lepton, the same classification as electrons. Muon has a bigger rest mass than electrons. Muon also decay into electron.

1.5.1 Quantum Numbers

Baryon

Baryon number is the number of baryons in a system minus the number of antibaryons. Baryon number is a quantum number, therefore, it is a conserved quantity. The number of baryons at an initial state is equal to the number of baryons at the end state.

All baryons have a baryon number of $+1$ and all antibaryon have a baryon number of -1.

$$n \longrightarrow p + e^- + \bar{\nu}_e$$
$$\text{baryon number:} +1 \longrightarrow +1 + 0 + 0 = 1$$

Lepton

Lepton consists of 3 flavours: electron, muon and tau. The same with quantum numbers, the each flavour of lepton number must be conserved in all interactions. Each lepton numbers assigns $+1$ to particles and -1 for antiparticles.

$$n \longrightarrow p + e^- + \bar{\nu}_e$$
$$\text{lepton number: } 0 \longrightarrow 0 + 1 - 1 = 0$$

Strange

Strange particles are produced through the strong nuclear interactions and decays through the weak nuclear interactions, this happens when kaons decay into pions. Strangeness is always created in particle-antiparticle pair. Strange quark and antiquark are denoted by s and $\bar{s}$ with strangeness of -1 and $+1$, respectively. Strangeness is a quantum number and is conserved but only through the strong nuclear interactions. In weak interactions, strangeness can change into $+1$, -1 or 0.

$$K^- + p \longrightarrow \Xi^0 + K^0$$
$$s\bar{u} + uud \longrightarrow uss + d\bar{s}$$
$$\text{strangeness: } -1 + 0 \longrightarrow -2 + 1 = -1$$

In the example, strangeness is conserved, so it must be interacting through the strong nuclear force. A pair or strange quark-antiquark is also created in this instance.

$$K^0 \longrightarrow \pi^+ + \pi^-$$
$$d\bar{s} \longrightarrow u\bar{d} + d\bar{u}$$
$$\text{strangeness: } +1 \longrightarrow 0 + 0 = 0$$

In this example, strangeness is not conserved, therefore, the interaction must have occurred through the weak nuclear force.

1.6 Quarks and Antiquarks

Quarks and antiquarks can have the following properties:

— charge
— baryon number
— strangeness

Baryon Numbers Explained

Baryon number is commonly defined as the number of baryon particles minus the number of baryon antiparticles. But, a more in-depth explanation is baryon numbers is defined as follows:

$$B = \frac{1}{3}(n_q - n_{\bar{q}}) \tag{7}$$

The formula equates the baryon number as one-third of the sum of quarks minus the antiquarks in a system. The simplified definition for the baryon number is generally easier to work with. This explains why quarks and antiquarks can have baryon numbers.

1.6.1 Common Baryons and Antibaryons

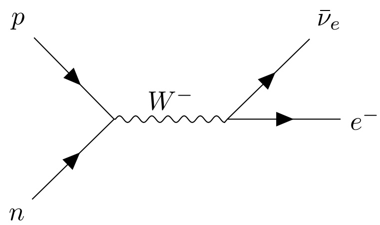
Baryons	Quark Composition
Proton	uud
Neutron	udd
Antiproton	$\bar{u}\bar{u}\bar{d}$
Antineutron	$\bar{u}\bar{d}\bar{d}$

1.6.2 Common Mesons

Mesons	Quark Composition
π^+	$u\bar{d}$
π^-	$d\bar{u}$
K^+	$u\bar{s}$
K^-	$s\bar{u}$
K^0	$d\bar{s}$
$\bar{K}^0$	$s\bar{d}$

1.6.3 Free Neutron Decay

Since proton is the only stable baryon, neutrons can decay into protons. Neutron decay only happens when when it is free from a nucleus.



$$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$$

1.7 Application of Conservation Laws

All particle interactions must follow the set of conservation laws in order for the interaction to be seen as valid. This is due to the general framework of quantum physics.

1.7.1 Conservation Laws

Conservation laws are set of rules that interactions follow. Conservation laws can be split into 2 types: classical quantities and quantum quantities. But, for the sake of simplicity, both will be called conservation laws.

These are quantities that must be conserved in any interaction:

1. Energy
2. Momentum
3. Charge
4. Baryon number
5. Electron lepton number
6. Muon lepton number
7. Tau lepton number
8. Strangeness (only in strong interactions)

1.7.2 Change of Quark Character

In β^- or β^+ decays, the quark characters, or flavours, can change. The change of quark flavour does not violate conservation laws. This also applies to any other interactions that change quark characteristics.

β Decay

$$\beta^- : udd \xrightarrow{W^-} uud + e^- + \bar{\nu}_e$$

$$\beta^+ : uud \xrightarrow{W^+} udd + e^+ + \nu_e$$