2 Quarks and Leptons

2.1 The Particle Zoo

Cosmic rays are high-energy particles that travel through space from the stars. Short-lived particles and antiparticles, and photons are created were created when cosmic rays enter the Earth's atmosphere.

They were thought to be from terrestrial radioactive substances, but it was disproved when found the ionising effect of the rays was significantly greater at 5000m than at ground level.

Most cosmic rays were **fast-moving protons** or **small nuclei**. They collide with gas atoms in the atmosphere, creating showers of particles and antiparticles that can be detected at ground level with **cloud chambers** or other detectors.

- The **muon** μ (heavy electron)
  - Negatively charged particle.
  - With rest mass over 200 times the rest mass of the electron.
- The **pion** π (pi meson)
  - Can be positively (π^+), negatively (π^-) charged, or neutral (π^0).
  - With rest mass greater than a muon but less than a proton.
- The **kaon** K (K meson)
  - Can be positively (K^+), negatively (K^-) or neutral (K^0).
  - With rest mass greater than a pion but less than a proton.

The existence of the **exchange particle** for the strong nuclear force between nucleons were predicted, with a range no more than 1fm. The predicted mass is between the electron and proton mass, they are called **mesons** for being in the middle of the two masses.

The π mesons were discovered from microscopic tracks found in photographic emulsion exposed to cosmic rays at high altitude, proving the prediction correct.

The **muon** was discovered from an unusually long track, indicating it lasted much longer than a strongly interacting particle should. Further investigation showed it to be a **heavy electron** that **decays through the weak interaction**.

Strange Particles

Further cloud chamber photographs showed the existence of short-lived particles known as **kaons**.

- Produced in twos through the **strong interaction** - similar to pions.
- When protons crash into nuclei at high speed, they travel far beyond the nucleus in which they originate before they decay.
- The decay of kaons took longer than expected and include **pions** as the product - this mean kaons must decay via the **weak interaction**.

These properties led to them being called **strange particles**.

Decay Pathways

Exotic particles can be created using **accelerators** in which protons **collide head-on** with other protons at high speed. The kinetic energy of the protons is converted into mass in the creation of new particles.

These created particles could be studied in **controlled conditions**, their **rest mass**, **charge** and **lifetimes** were measured. Their decay modes were worked out.

- A **kaon** can decay into
  - Pions
  - A muon and an antineutrino
  - An antimuon and a neutrino
- A **charged pion** can decay into
  - A muon and an antineutrino
  - An antimuon and a neutrino
- A π^0 **meson** can decay into **high-energy photons**.

Decays always obey the conservation rules for energy, momentum, and charge.

2.2 Particle Sorting

The new particles created through **high-energy interactions** (apart from the neutrino) decay into other particles and anti particles.

- **Charged pions** were often produced in pairs, leading to the conclusion that the π^+ and π^- mesons are a particle-antiparticle pair.
- Same for **charged kaons**.

Particle	Relative charge	Rest energy/MeV	Interaction
proton p	$+1$	938	strong, weak, electromagnetic
neutron n	0	939	strong, weak
electron e^-	-1	0.5	weak, electromagnetic
neutrino ν	0	0	weak
pions π^+, π^0, π^-	$+1, 0, -1$	$140, 135, 140$	strong, electromagnetic (π^+, π^-)
kaons K^+, K^0, K^-	$+1, 0, -1$	$494, 498, 494$	strong, electromagnetic (K^+, K^-)

The particle symbol for **antiparticles** as a $\overline{\text{bar above them}}$, except for the **positron** e^+ and **antimuon** μ^+ which have their own symbols. The **charged pions** are antiparticles of each others.

Particles Classification

Particles can be divided into two groups according to whether or not they **interact through the strong interaction**.

Hadrons are particles and antiparticles that can interact through the strong interaction.

- Hadrons can interact through **all four fundamental interactions**.
- Including protons, neutrons, π and K mesons.
- Apart from the stable proton, hadrons tend to decay through the weak interaction.

Leptons are particles and antiparticles that do not interact through the strong interaction.

- Leptons interact through the **weak** interaction, **gravitational** interaction and **electromagnetic** interaction (if charged) only.
- Including electrons, muons and neutrinos.

The **Large Hadron Collider** is a ring-shaped accelerator that boosts the kinetic energy of charged particles. Particles collide head-on to produce new particles.

$$\text{total energy of particles} = \text{rest energy of particles} + \text{kinetic energy of particles}$$
$$\text{rest energy of products} = \text{total energy before} - \text{kinetic energy of products}$$

A collision can produce a range of products, as long as their total energy does not exceed the total energy before the collision, provided **conservation rules** are obeyed.

Hadron Classification

Short-lived particles created through the **strong interaction** are hadrons. Some decay into protons as well as into pions, whereas **kaons** never decay into protons.

Hadrons can be divided into two groups

- **Baryons** are protons and all other hadrons that decay into protons, directly or indirectly.
- **Mesons** are hadrons that do not include protons in their decay products.

Baryons and mesons are composed of smaller particles called **quarks** and **antiquarks**.

2.3 Leptons at Work

Leptons and **antileptons** can interact to produce hadrons - an **electron-positron annihilation event** produces a quark and a corresponding antiquark moving away in opposite directions, producing a **shower of hadrons** in each direction.

Neutrinos are produced when particles in accelerators collide.

- Travel almost as fast as light.
- Billions passing through the Earth every second with **almost no interaction**.

Experiments showed that neutrinos and antineutrinos produced in beta decays were different from those produced in muon decays.

- Neutrinos and antineutrinos from muon decays create only muons and no electrons.
- If there were only one type of neutrino and antineutrino, equal number of electrons and muons would be produced.

We use symbol ν_μ for the **muon neutrino** and ν_e for the **electron neutrino**.

Lepton Rules

- Leptons can be changed into other lepton through the **weak interaction**.
- Produced or annihilated in **particle-antiparticle interactions**.
- Experiments indicate they don't break down into non-leptons - they appear **fundamental**.

An interaction between a lepton and a hadron, a neutrino or antineutrino can change into or from a **corresponding charged lepton**. An electron neutrino can interact with a neutron to produce a proton and an electron.

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

In **muon decay**, the muon changes into a muon neutrino.

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

- An electron is created to conserve charge.
- A corresponding antineutrino is created to conserve **lepton number**.

The **lepton number** is $+1$ for any lepton, -1 for any antilepton, 0 for any non-lepton.

Lepton number is conserved in any change.

2.4 Quarks and Antiquarks

Strange particles all decay through the weak interaction

- **Kaons** decay into pions only.
- Other particles such as the Σ particle
  - Have rest masses which were always greater than the proton's rest mass.
  - Decay in sequence or directly into protons and pions.

Strange particles are created in twos.

To explain why certain reactions were not observed, a **strangeness number** was introduced for each particle and antiparticle so that strangeness is conserved in strong interactions.

Starting with $+1$ for the K^+ meson. The strangeness for other strange particles and antiparticles can then be deduced from the observed reactions.

- Strangeness is **always conserved in strong interaction**.
- And can change by $0, +1, -1$ in weak interactions.

The properties of **hadron**, such as charge, strangeness, and rest mass can be explained by assuming they are composed of smaller particles known as **quarks and antiquarks**.

	up u	down d	strange s
charge Q	$+2/3$	$-1/3$	$-1/3$
strangeness S	0	0	-1
baryon number B	$+1/3$	$+1/3$	$+1/3$

Quark Combinations

Mesons are hadrons each consisting of a quark and an antiquark.

- A π^0 meson can be any quark-corresponding antiquark combination/
- Each pair of charged meson is a particle-antiparticle pair.
- There are two uncharged kaons: K^0 and $\bar{K^0}$.

Baryons are hadrons that consist of three quarks.

- Proton: uud
- Neutron udd
- A Σ particle is a baryon containing a strange quark.
- The **proton** is the only stable baryon. A free neutron decays into a proton in a β^- decay.

In terms of quarks, in β^- decay, a down quark changes to an up quark, releasing an electron and an electron neutrino. The β^+ case is similar.

2.5 Conservation Rules

Particles and antiparticles obey certain conservation rules when they interact.

- **Conservation of energy and conservation of charge** apply to all changes in science. The conservation of energy includes the rest energy of the particles.
- **Conservation of lepton number -** in any change, the total lepton number before the change is equal to the total lepton number for that branch after the change.
- **Conservation of strangeness -** in any strong interaction, strangeness is always conserved.

By assigning a **baryon number** of $+1$ to any baryon, -1 to any antibaryon, and 0 to any meson or lepton. We can state

- **Conservation of baryon number -** for any reaction, the baryon number is conserved.

Conservation rules for particle and antiparticle interactions and decays are essentially **particle-counting rules** based on reactions observed.