Section 1.3.4 – The Standard Model

Cosmic Radiation

It took the scientific community over a century to construct a universally accepted periodic table. Thanks to the work of Dmitri Mendeleev and others, today we have an excellent system of categorising elements based upon atomic number and electronic configuration.

J J Thomson discovered the electron in the late 19th century and this was in turn followed by the discovery of the proton by Ernest Rutherford and the neutron by James Chadwick in the early 20th century.

At a similar time, cosmic rays were discovered in 1912 by Victor Hess, when he found that an electroscope discharged more rapidly as he ascended in a balloon. He attributed this to a source of radiation entering the atmosphere from above, and in 1936 was awarded the Nobel Prize for his discovery.

When cosmic rays, which are mostly protons, enter our atmosphere they engage in a range of different collisions, generating a range of charged particles and gamma rays at the Earth's surface, as can be seen in **Figure 1**.

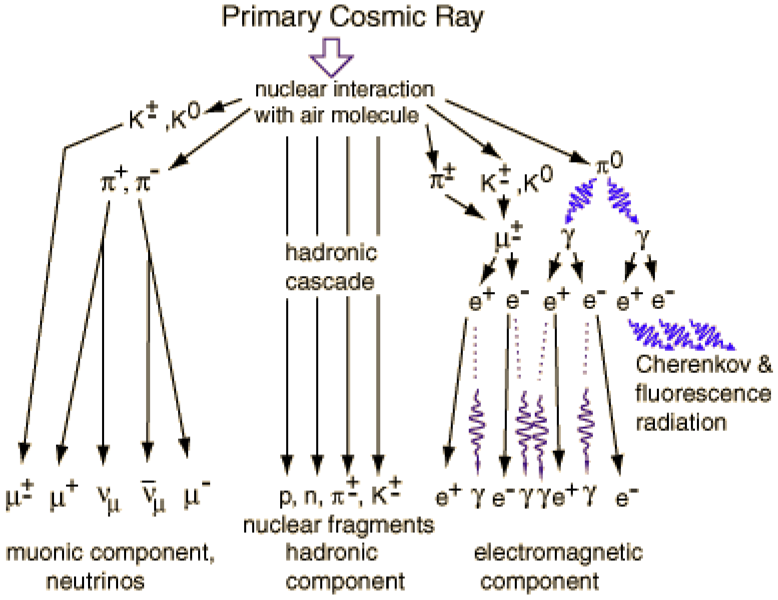

Figure 1

Pair Production

In 1933 Carl Anderson observed the **pair production** of an electron and its **antiparticle**, the **positron**. The pair were produced from the energy of a **gamma ray** following a collision with a nucleus, as seen in **Figure 2**.

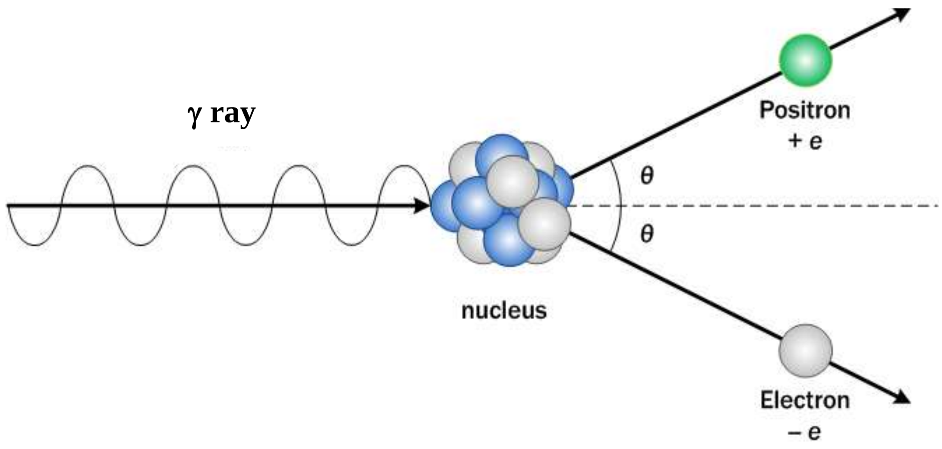

Figure 2

In this scenario the energy of the gamma ray is converted into mass, using $E=mc^2$.
As the charge needs to remain neutral, two particle of oposite signs are produced.

NB: Pair production is a phenomenon of nature where **energy is direct converted to matter.**

For pair production to occur the electromagnetic energy of the photon (gamma ray) must be above a threshold energy:

$$\begin{aligned}\text{Threshold energy} &= mc^2\text{ (electron)} + mc^2\text{(positron)}\\ &= [9.11 \times 10^{-31} \times (3.0 \times 10^8)^2] + [9.11 \times 10^{-31} \times (3.0 \times 10^8)^2]\\ &= 1.6398 \times 10^{-13}\text{ J}\\ &= 1.02\text{ MeV}\end{aligned}$$

NB: for every particle that exists there is an antimatter particle of equal mass and opposite charge.

Pair annihilation

In the event that a positron interacts with an electron, the reverse process to pair production occurs. That is, both particles ar **annihilated** and the complete conversion of their mass back to pure energy occurs (according to the $E=mc^2$ formula). The end products is two oppositely directed 0.511 MeV gamma rays (photons). This is depicted in **Figure 3.**

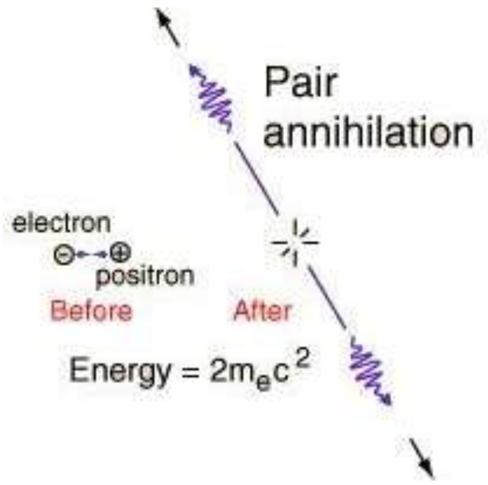

Figure 3

The Standard Model

The Standard Model of particle physics is the theory describing three of the four known fundamental forces in the universe (the electromagnetic, weak, and strong interactions).

Everything in the universe is found to be made from a few basic building blocks called **fundamental particles**, governed by **four fundamental forces**. All matter around us is made of elementary particles, the building blocks of matter. These particles occur in two basic types called **quarks** and **leptons**.

Each group consists of six particles, which are related in pairs, or “**generations**”.
All stable matter in the universe is made from particles that belong to the first generation; any heavier particles quickly decay to the next most stable level.

The six quarks are paired in the three generations – the “**up quark**” and the “**down quark**” form the first generation, followed by the “**charm quark**” and “**strange quark**”, then the “**top quark**” and “**bottom quark**”.

The six leptons are similarly arranged in three generations – the “**electron**” and the “**electron neutrino**”, the “**muon**” and the “**muon neutrino**”, and the “**tau**” and the “**tau neutrino**”.

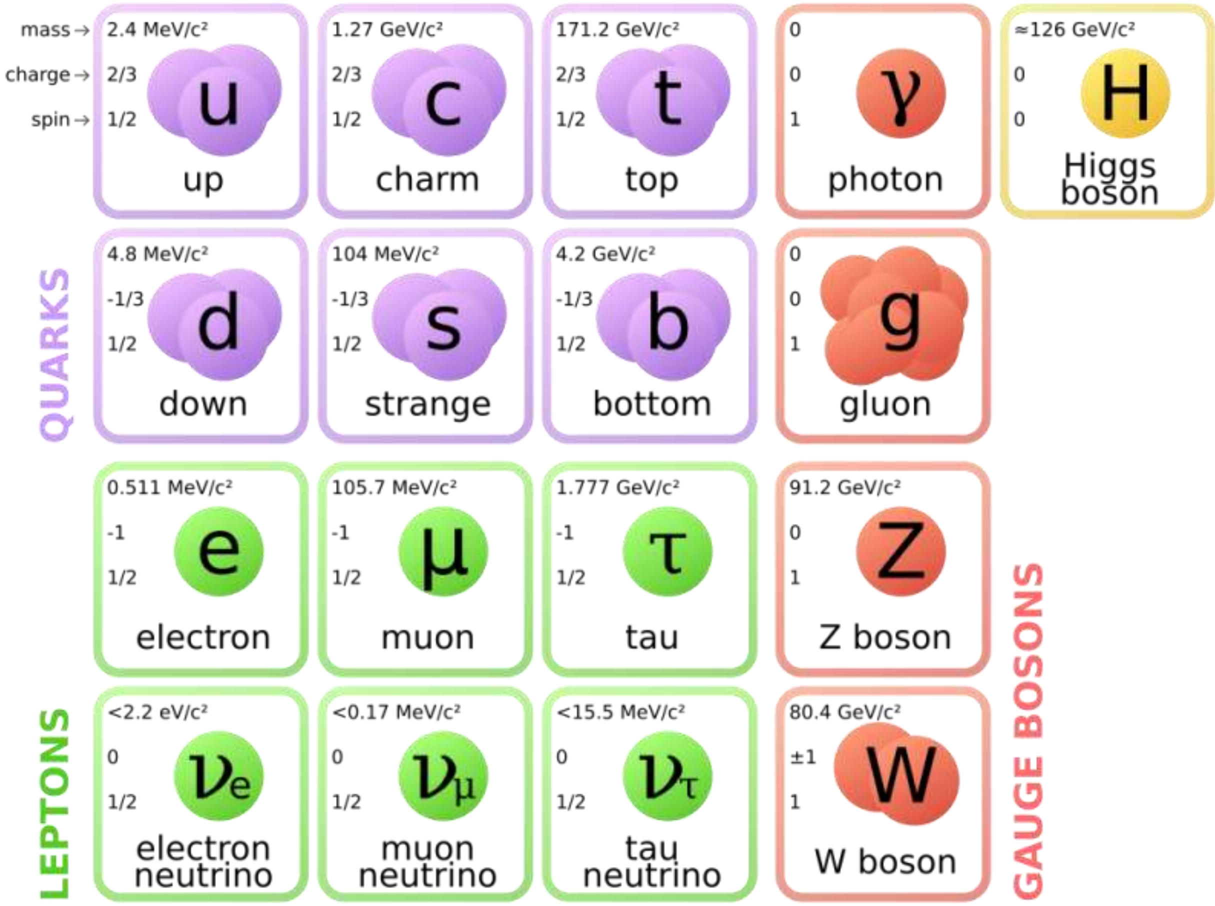

Figure 4

NB: The electron, the muon and the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass.

Forces and carrier particles

There are four fundamental forces at work in the universe: the **strong force**, the **weak force**, the **electromagnetic force**, and the **gravitational force**.

Three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called "**bosons**". Particles of matter transfer discrete amounts of energy by exchanging bosons with each other.

Each fundamental force has its own corresponding boson – the **strong force** is carried by the "**gluon**", the **electromagnetic force** is carried by the "**photon**", and the "**W and Z bosons**" are responsible for the **weak force**. Although not yet found, the "**graviton**" should be the corresponding force-carrying particle of **gravity**.

Classification of Matter

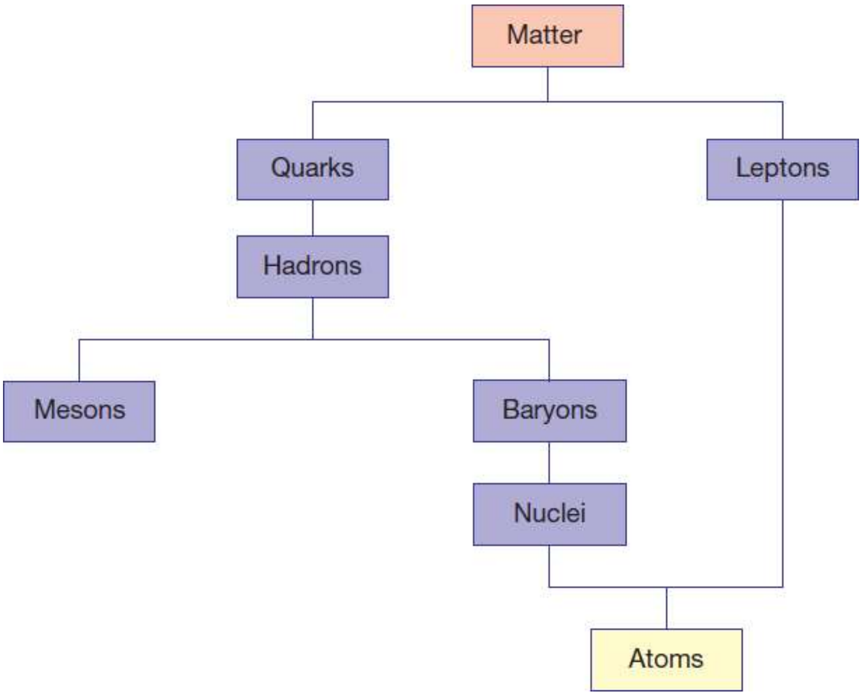

Figure 5

Leptons are the simplest and lightest of the subatomic particles, they are a fundamental particles, that is, they have no internal structure.

Hadrons are distinctive because they are much heavier than the leptons, but much more importantly they all have an internal structure. Hadrons are made up of different **combinations of quarks.**

Hadrons that are a combination of **two quarks** are called **mesons**. There are over 60 different types of mesons. They play a role in nuclear interactions, but have very short half-lives, so they are very difficult to detect. Each meson also has an antiparticle.

Hadrons that are a combination of **three quarks** and are called **baryons**. Baryons include the proton and neutron as well as about 70 other different particles. Only the proton and neutron are stable, with all other baryons having extremely short half-lives. Each baryon also has its own antiparticle.

Why a quark model?

The science of spectroscopy originated in the 17th century and has been perfected over time with improved optical devices and techniques. As the name suggests spectroscopy is associated with the spectrum of light.

Figure 6

There are two techniques used:

1. Emission Spectroscopy

Emission spectroscopy is the process whereby electrons within an atom are excited to a higher energy level via a high current or thermal source. Such an excited atom is unstable and the excited electrons soon return to their "ground state" via the emission of a photon.

The energy of the emitted photons is equal to the difference between the associated energy levels. The frequency of each photon (ie. colour) therefore provides information about the atomic structure of the sample.

Figure 7

NB: An emission spectrum is unique to a gas sample much like a fingerprint is unique to a person.

2. Absorption Spectroscopy

Absorption spectroscopy as the name suggests is a process whereby white light is directed through a gas sample and certain frequencies (ie. colours) are absorbed. Again only energies corresponding to the energy transitions within the atom are permitted.

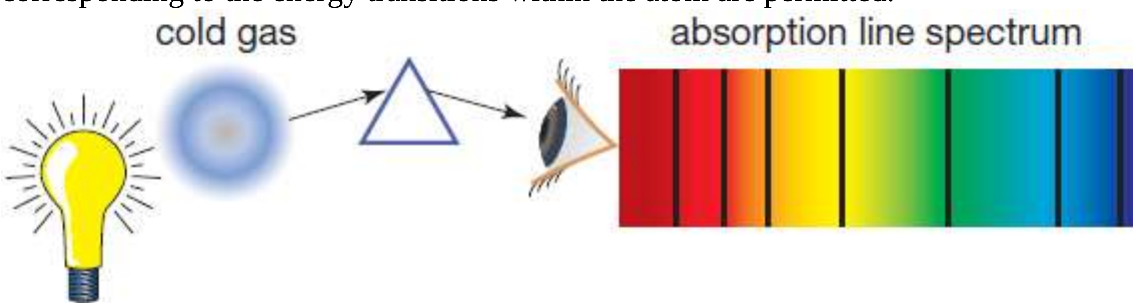

Figure 8

NB: An absorption spectrum is the photographic negative of an emission spectrum.

Both spectral analysis techniques allowed Physicist to investigate the structure of the atom. Likewise the energy of emitted alpha particles via radioactive decay also provided information about the internal structure of the nucleus.

During the 1960s it was discovered that when protons and neutrons were hit by a beam of particles, a type of spectra was evident, much like molecules, atoms and nuclei. This meant that protons and neutrons are made up of even smaller particles. This was the beginning of the **quark model.**

Quark	Symbol	Charge	Multiple of proton mass	First observed
Up	u	$+\frac{2}{3}$	0.003	1968
Down	d	$-\frac{1}{3}$	0.006	1968
Charm	c	$+\frac{2}{3}$	1.3	1974
Strange	s	$-\frac{1}{3}$	0.1	1968
Top	t	$+\frac{2}{3}$	184	1995
Bottom	b	$-\frac{1}{3}$	4.5	1977

Synchrotron Light

The Australian synchrotron is an advanced third generation synchrotron that accelerates groups of electrons to an energy of 3 GeV.

Electrons are generated in the centre (electron gun) and accelerated to 99.9997% of the speed of light by the linear accelerator (linac). The electrons are then transferred to the booster ring, where they are increased in energy. They are then transferred to the outer storage ring.

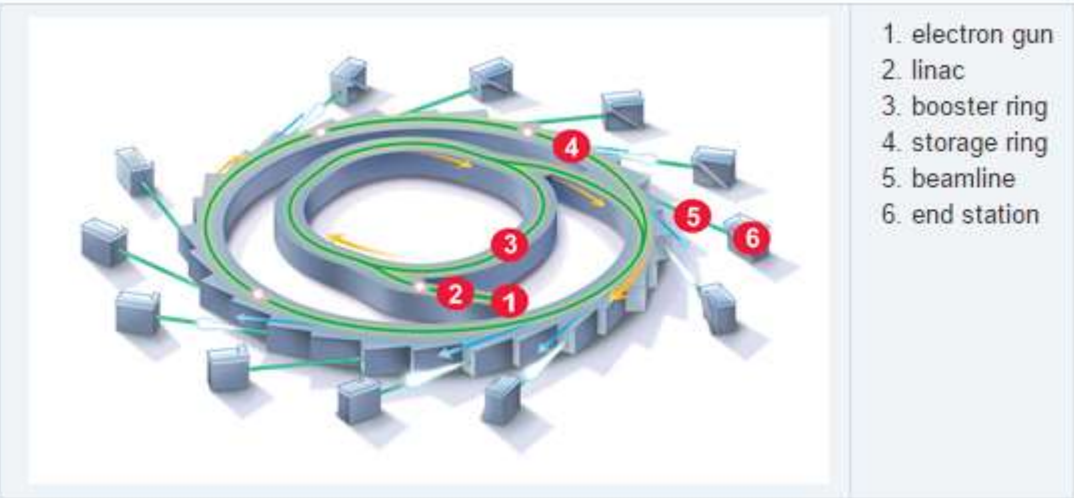

Figure 9

The electrons are circulated around the storage ring by a series of magnets separated by straight sections. As the electrons are deflected through the magnetic field created by the magnets, they give off electromagnetic radiation, so that at each bending magnet a beam of synchrotron light is produced.

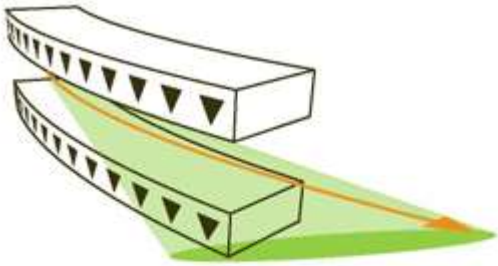

Figure 10

This **synchrotron radiation** can be captured and focussed to a specific wavelength appropriate for a particular technique.

NB: Synchrotron radiation is emitted along the tangent of the circular path.