The Standard Model

1 Introduction

At the subatomic level, scattering experiments are fully consistent with a model where the basic building blocks of matter are **point-like** entities with no discernible size, which we call 'fundamental particles'.

There are twelve matter particles, all of which are **spin-half fermions** with positive parity. You will already be familiar with one example – the **electron**. Scattering experiments involving electrons can resolve no structure to that particle down to length scales of less than $\sim 10^{-18}\,\mathrm{m}$.

The proton and neutron are *not* point-like, and so are not fundamental particles. Scattering experiments show that each has non-zero size of order $10^{-}15\,\mathrm{m}$. Both the proton and the neutron have sub-structure which has been probed by scattering experiments at high $\gg\ \mathrm{GeV}$ energies. These 'deep inelastic scattering' experiments are described in more detail later.

The twelve fundamental matter particles are shown in Table 1. Each finds itself in one of two categories – it is either a **quark** or a **lepton** depending on whether it does or does not interact via the strong nuclear force.

1.1 Leptons

The electron is an example of a **lepton**. Lepton is a historical name meaning 'light particle', and indeed the electron is much lighter than e.g. the proton or the neutron. However the defining feature of the leptons *not* their mass – there do exist relatively heavy leptons – but is that they are the matter particles which have **no strong interactions**. We know that electrons can have no strong interactions, otherwise our model of the atomic structure would be horribly wrong. None of the other leptons have strong interactions either.

The leptons come in two varieties. The electron is one of the three **charged leptons**; each has electric charge (of the same magnitude but of the opposite sign to that of the proton). The electron has two heavier cousins, the **muon** μ^- and the **tau** τ^- leptons. Each has the same spin and charge as the electron, but they have larger masses. I can't tell you *why* these heavier cousins exist – there is no model that explains this pattern – but empirically we find that they are there.

Muons are relatively short-lived (mean proper lifetime $\tau = 2.2 \times 10^{-10}\,\mathrm{s}$), and so do not play a big role in every day life. So it is easy to think that this heavier copy of the electron is a rather exotic relative. However muons are more common-place than you might think – they are produced by the interaction of cosmic rays from the upper atmosphere, and so there is about one muon passing through your body every second. Taus are heavier again, and have even shorter lifetimes ($2.9 \times 10^{-13}\,\mathrm{s}$).

There are also three neutral leptons called **neutrinos**. We have already met one of these three – the ν_e – in the context of nuclear beta decays

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

and we met it's anti-particle (the $\bar{\nu}_e$) in the solar pp fusion reaction:

$$p + p \to {}^2_1\mathrm{H} + e^+ + \bar{\nu}_e.$$

This example is the neutrino that partners the electron: ν_e. There are two other neutrinos, ν_μ and ν_τ that partner the other two charged leptons.

Neutrinos have very small mass, and were for a long time believed to be totally massless. The subsequent discovery of the phenomenon of **neutrino flavour oscillations** – discussed in its own section – shows that the mass must be non-zero, but still very small. All of these three neutrinos have mass less than a single electron-volt. As well as being almost massless, neutrinos have few interactions. For a start as leptons they do not feel the strong nuclear force. Also they are electrically neutral and so do not interact through the electromagnetic force. If they did not interact with anything at all we would never know about their existence. But fortunately they do interact with the other remaining force of particle physics – the **weak nuclear force**. Because this force is week at all but the highest energies neutrinos can pass very large distances through matter without interacting in any way.

These then are the six leptons of the standard model – three charged leptons (e^-, μ^-, τ^-) and three neutrinos. Experiment shows, that every matter particle has an **anti-particle** which has the same mass but has the opposite charges as its partner particle. So the anti-electron has positive charge $Q = +1$ is known as the **positron**, and is given the symbol e^+ [1]. Similarly there is an anti-muon μ^+ with mass equal to that of the muon μ^-, and an anti-tau τ^+. Similarly there are three anti-neutrinos: $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$.

The type of lepton is known as its **flavour**. There are three flavours of charged leptons: (e^-, μ^-, τ^-), and associated with them the three flavours of neutrino: ν_e, ν_μ and ν_τ.

1.2 Quarks

The quarks are also spin-half, point-like particles. Unlike the leptons they *do* interact via the **strong nuclear force**.

Like the leptons, the quarks come in three 'generations' (Table 1). The first generation contains the 'up' (u) and 'down' (d) quarks, the constituents of the proton

[1] It can be surprisingly easy to forget the convention that the anti-particle is the *positively* charged object.

	Quarks		Leptons	
Generation	$Q=-\frac{1}{3}$	$Q=+\frac{2}{3}$	$Q=-1$	$Q=0$
First	down (d) $\sim$ 2.5 MeV	up (u) $\sim$ 5 MeV	electron (e) 0.511 MeV	e neutrino (ν_e) <1 eV
Second	strange (s) ~ 101 MeV	charm (c) 1270 MeV	muon (μ) 105.7 MeV	μ neutrino (ν_μ) <1 eV
Third	bottom (b) 4200 MeV	top (t) 172 GeV	tau (τ) 1777 MeV	τ neutrino (ν_τ) <1 eV

Table 1: The quark and lepton families, their masses in natural units (i.e. MeV means MeV/c^2) and their charges Q in units of the proton charge.

($p = uud$) and neutron ($n = udd$). You can confirm that the constituent quark charges – $\frac{2}{3}$ for the up quark and $-\frac{1}{3}$ do indeed add up to those of the proton and the neutron.

Again the second generation contains heavier 'copies' of the first generations. The second generation contains two quarks, the partners of u and d called **charm** (c, $Q=\frac{2}{3}$) and strange (s, $Q=-\frac{1}{3}$) respectively.

The third generation is heavier again – the bottom quark[2] is the charge $-\frac{1}{3}$ cousin of the d quark. Top quark has $Q=\frac{2}{3}$ and is the heavier cousin to the u quark. It is notable that top quark is really very heavy; its mass of $\approx 174\,\mathrm{GeV}$ is more than 300,000 times heavier than the electron.

The second and third generation quarks are not found in everyday matter, but have a brief existence after creation in high-energy interactions before they decay to lighter particles.

The type of quarks is known as it's **flavour**; there are then six flavours of quark: u, d, c, s, t, b.

2 Force-carrying particles

At the microscopic level, experiments are consistent with a model in which forces are conveyed by point-like particles or **quanta**. As **virtual particles** these force-carrying particles are exchanged, leading to a change in momentum of those emitting/absorbing the force-carrier. The electromagnetic, strong nuclear and weak nuclear force-carriers are **spin-1 bosons** (see Table 2).

[2]Some people think that the word 'bottom' is too coarse and so call this fermion the 'beauty' quark.

Force	Quantum	Symbol	Mass	Spin	Rel. strength	Range
Electromagnetic	Photon	γ	0	1	$1/137$	∞
Strong	Gluon ($\times 8$)	g	0	1	1	$\sim 10^{-15}$ m
Weak	$W^{\pm}$		80.4 GeV	1	$1/29$	$\sim 10^{-18}$ m
	Z^0		91.2 GeV	1		
Gravity	?Graviton?	G	0	2		∞

Table 2: The force-carrying particles γ, g, $W^{\pm}$ and Z^0 of the Standard Model (and the proposed graviton G). A spin-2 graviton has been hypothesised, but the gravitational force is too weak to allow the detection of an individual graviton with current technology.

Gravity

3 Composites of quarks – hadrons; mesons and baryons

Unlike leptons, the quarks *do* feel the strong nuclear force. A consequence of this is that the inter-quark strong force is so powerful that one does *not* observe bare quarks in nature. Instead quarks are only found bound up – **confined** – in composite objects known as **hadrons**.[3]

One observes two different ways quarks can get together to form composite objects.

3.1 Baryons

Objects made out of three quarks (of any flavour) qqq can exist as composites known as **baryons**. Examples of some baryons and their associated spin and quark content are:

3.2 Mesons

The second way that quarks get together to form composite objects is as a quark + anti-quark system (of any flavour) $q\bar{q}$. Examples of mesons can be found in Table **??**

[3] Hadron originally was intended to mean 'stout particle' but now means a composite particle made out of quarks.

Name	Symbol	Quarks	Spin/Parity	Mass/MeV	Lifetime
Proton	p	uud	$\frac{1}{2}^+$	938.3 MeV	∞?
Neutron	n	udd	$\frac{1}{2}^+$	939.6 MeV	886 s
Lambda baryon	Λ^0	uds	$\frac{1}{2}^+$	1116 MeV	2×10^{-10} s
Neutral delta baryon	Δ^0	udd	$\frac{3}{2}^+$	1232 MeV	[$\Gamma \approx 120$ MeV]

Table 3: Examples of some baryons. Note that the Δ^0 baryon has the same quark flavour content as the neutron, but is a completely different state (its mass, spin and decay modes differ from those of the neutron).

Name	Symbol	Quarks	Spin/Parity
pion	π^+	$u\bar{d}$	0^-
pion	π^-	$d\bar{u}$	$0-$
pion	π^0	$d\bar{d}/u\bar{u}$ mix	0^-
kayon	K^+	$u\bar{s}$	0^-
J/psi	J/Ψ	$c\bar{c}$	1^-
upsilon	Υ	$b\bar{b}$	1^-

Table 4: Examples of some baryons. Note that the Δ^0 baryon has the same quark flavour content as the neutron, but is a completely different state (its mass, spin and decay modes differ from those of the neutron).

3.3 The quark structure of the hadrons

There are a vary large number of different baryons and mesons, (collectively hadrons) with different quark content, there are. We shalln't attempt to tabulate them all. If we need to know properties we can look them up in the particle data group's book, which can also be found online at pdg.lbl.gov.

MORE

4 Deep inelastic scattering

5 Books

- *"Nuclear and Particle Physics: An Introduction"* by Brian Martin
- *"Nuclear and Particle Physic"* by W.E. Burcham and M. Jobes