PHYS 30121 NUCLEAR AND PARTICLE PHYSICS

PARTICLES OF THE STANDARD MODEL

The building blocks of matter in the standard model are the six flavours of quark and six flavours of lepton (and their antiparticles). The quarks all have baryon number $B = +\frac{1}{3}$. Their other properties are:

quark	I_3	S	C	$\widetilde{B}$	T	Q	mass		lifetime
t	0	0	0	0	+1	$+\frac{2}{3}$	173 GeV		$\sim 10^{-25}$ s
b	0	0	0	−1	0	$-\frac{1}{3}$	4.2 GeV		$\sim 10^{-13}$ s
c	0	0	+1	0	0	$+\frac{2}{3}$	1.3 GeV		$\sim 10^{-13}$ s
s	0	−1	0	0	0	$-\frac{1}{3}$	95 MeV	($\sim$ 450 MeV)	$\sim 10^{-10}$ s
u	$+\frac{1}{2}$	0	0	0	0	$+\frac{2}{3}$	2.5 MeV	($\sim$ 350 MeV)	
d	$-\frac{1}{2}$	0	0	0	0	$-\frac{1}{3}$	5 MeV	($\sim$ 350 MeV)	

The flavour quantum numbers ("charges") listed here are: third component of isospin I_3, strangeness S, charm C, "bottomness" $\widetilde{B}$, and "topness" T. The EM charge is related to these by

$$Q = I_3 + \tfrac{1}{2}\left(B + S + C + \widetilde{B} + T\right).$$

(The quantum numbers S and $\widetilde{B}$ labelling the quarks with negative EM charges are defined to be negative so that the sum of these numbers appears here.) This can also be written in the form

$$Q = I_3 + \tfrac{1}{2}Y,$$

where the hypercharge is defined as

$$Y = B + S + C + \widetilde{B} + T.$$

These quantum numbers are conserved in strong and EM processes.

The masses listed above are the values appropriate to high-energy processes. For the three light quarks, I have also given the low-energy "effective" values, relevant to hadron structure. The antiquarks have opposite values for all these charges, and identical masses and lifetimes (as a consequence of the CPT theorem).

The leptons all have lepton number $L = +1$. Their other properties are:

lepton	L_e	L_μ	L_τ	Q	mass	lifetime
τ^-	0	0	+1	−1	1.78 GeV	3×10^{-13} s
μ^-	0	+1	0	−1	106 MeV	2×10^{-6} s
e^-	+1	0	0	−1	0.511 MeV	
ν_τ	0	0	+1	0	< 2 eV	
ν_μ	0	+1	0	0	< 2 eV	
ν_e	+1	0	0	0	< 2 eV	

The lepton favour numbers are conserved by the EM interaction, and by the weak interaction as observed on normal length scales (10s of metres or less). The antileptons have opposite values for all these charges, and identical masses. (I am assuming here that antineutrinos are distinct from neutrinos.)

Fermions and antifermions have opposite intrinsic partities. By convention, the fermions listed above all have positive intrinsic parity.

The forces between these particles are mediated by bosons. The properties of these are:

force	boson	J^{PC}	Q	mass	lifetime
strong	g	1^-	0	0	
EM	γ	1^{--}	0	0	
weak	W^-	1	−1	80.4 GeV	$\sim 10^{-25}$ s
	W^+	1	+1	80.4 GeV	$\sim 10^{-25}$ s
	Z^0	1	0	91.2 GeV	$\sim 10^{-25}$ s
Higgs	H^0	0	0	126 GeV	$> 10^{-23}$ s

The quarks also carry a three-valued quantum number: colour (r, g, b). This is the charge that gluons couple to. Gluons themselves are coloured, coming in eight types ($r\overline{g}$ etc).

The weak interaction couples to left-handed fermions and right-handed antifermions in the weak isospin doublets:

$$\begin{pmatrix} u \\ d' \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix}, \quad \begin{pmatrix} t \\ b' \end{pmatrix}, \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix},$$

where the weak eigenstates, d', s' and b', are mixtures of the mass eigenstates, d, s and b. The observation of neutrino oscillations over long distances shows that the neutrinos, ν_e, ν_μ and ν_τ, are mixtures of their mass eigenstates, ν_1, ν_2 and ν_3.

The fermions can be organised into three generations:

$$(u,\, d,\, \nu_e,\, e^-), \quad (c,\, s,\, \nu_\mu,\, \mu^-), \quad (t,\, b,\, \nu_\tau,\, \tau^-).$$

The first of these contains the constituents of "ordinary" matter. The other two consist of heavier copies which, except for the neutrinos, are unstable. Mixing between the generations means that only particles built out of the first generation – nuclei along the line of stability and atoms containing them – are stable against weak decays.

The left-handed couplings of the weak interaction violate parity (P) and charge conjugation (C) symmetries. If there were only one or two generations, the combination CP would be preserved. However, mixing between three or more generations can introduce CP violation into the weak interaction. Although this effect is small, it has been observed, and it is required to explain the origin of the matter we see around us in the universe.

To avoid violating current conservation for the EM and weak interactions, the charges of the fermions must satisfy certain anomaly-cancellation conditions. One of these is that the sum of all fermion charges must be zero. This is satisfied by each generation of fermions:

$$\sum_f Q_f = 3\left(+\tfrac{2}{3}\right) + 3\left(-\tfrac{1}{3}\right) + (-1) + 0 = 0.$$

Right-handed fermions and left-handed antifermions are singlets and so they do not couple to W and Z bosons. However they do couple to the Higgs boson, which can change the chirality of a particle from right-handed to left-handed or *vice versa*. The field corresponding to the Higgs boson has a nonzero value everywhere in space. Coupling to this field is what generates masses for the fermions without spoiling conservation of the left-handed current of the weak interaction. It also, through the more complicated Brout-Englert-Higgs mechanism, leads to the masses of the W and Z bosons.

In quantum chromodynamics, the strong interaction is sufficiently strong at low energies, that the vacuum is filled with a condensate of light quark-antiquark pairs. This condensate acts in a similar way to the Higgs field, generating effective masses for the light quarks of about 350 MeV. It can also explain why pions are much lighter than expected for simple $q\overline{q}$ states. (Their masses are about 140 MeV not $\sim$ 600 MeV.) Pions are therefore doubly important: they mediate the longest-range strong forces in nuclei and they carry a “memory” of the symmetries of QCD (the theory of quarks and gluons).

Mike Birse (December 2014)