Introduction to Particle Physics

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Quantum Fields and Fundamental Forces
Imperial College
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Contents

Recommended Books

⋆ G. D. Coughlan, J.E. Dodd and B.M. Gripaios, *The Ideas of Particle Physics, an introduction for scientists*, 3rd edition CUP (2006).

- D. H. Perkins, *Introduction to High energy Physics,* 4th ed., CUP (2000).
- B. R. Martin and G. Shaw, *Particle Physics,* 2nd ed., Wiley (1998).
- Abraham Pais, *Inward Bound: Of Matter and Forces in the Physical World*, Clarendon Press, (1988).

1. Introduction to Symmetry and Particles

Symmetry simplifies the description of physical phenomena. It plays a particularly important role in particle physics, for without it there would be no clear understanding of the relationships between particles. Historically, there has been an "explosion" in the number of particles discovered in high energy experiments since the discovery that atoms are not fundamental particles. Collisions in modern accelerators can produce cascades involving hundreds of types of different particles: $p, n, \Pi, K, \Lambda, \Sigma \dots$ etc.

The key mathematical framework for symmetry is group theory: symmetry transformations form groups under composition. Although the symmetries of a physical system are not sufficient to fully describe its behaviour - for that one requires a complete dynamical theory - it is possible to use symmetry to find useful constraints. For the physical systems which we shall consider, these groups are smooth in the sense that their elements depend smoothly on a finite number of parameters (called co-ordinates). These groups are Lie groups, whose properties we will investigate in greater detail in the Particle Symmetries lectures. We will see that the important information needed to describe the properties of Lie groups is encoded in "infinitesimal transformations", which are close in some sense to the identity transformation. The properties of these transformations can be investigated using (relatively) straightforward linear algebra. This simplifies the analysis considerably. We will make these rather vague statements more precise in the lectures.

Examples of symmetries include

i) Spacetime symmetries: these are described by the Poincaré group. This is only an approximate symmetry, because it is broken in the presence of gravity. Gravity is the weakest of all the interactions involving particles, and we will not consider it here.

ii) Internal symmetries of particles. These relate processes involving different types of particles. For example, isospin relates u and d quarks. Conservation laws can be found for particular types of interaction which constrain the possible outcomes. These symmetries are also approximate; isospin is not exact because there is a (small) mass difference between m_u and m_d. Electromagnetic effects also break the symmetry.

iii) Gauge symmetries. These lead to specific types of dynamical theories describing types of particles, and give rise to conserved charges. Gauge symmetries if present, appear to be exact.

1.1 Elementary and Composite Particles

The fundamental particles are quarks, leptons and gauge particles.

The *quarks* are spin 1/2 fermions, and can be arranged into three families

			Electric Charge (e)
u (0.3 GeV)	c (1.6 GeV)	t (175 GeV)	$\frac{2}{3}$
d ($\approx$ 0.3 GeV)	s (0.5 GeV)	b (4.5 GeV)	$-\frac{1}{3}$

The quark labels u, d, s, c, t, b stand for up, down, strange, charmed, top and bottom. These labels are referred to as *flavours*, so there are six flavours of quark. The quarks carry a fractional electric charge. Each quark has three *colour* states. Quarks are not seen as free particles, so their masses are ill-defined (the masses above are "effective" masses, deduced from the masses of composite particles containing quarks).

The *leptons* are also spin 1/2 fermions and can be arranged into three families

			Electric Charge (e)
e^- (0.5 MeV)	μ^- (106 MeV)	τ^- (1.8 GeV)	-1
ν_e (< 10 eV)	ν_μ (< 0.16 MeV)	ν_τ (< 18 MeV)	0

The leptons carry integral electric charge. The muon μ and taon τ are heavy unstable versions of the electron e. Each flavour of charged lepton is paired with a neutral particle ν, called a neutrino. The neutrinos are stable, and have a very small mass (which is taken to vanish in the standard model).

All these particles have *antiparticles* with the same mass and opposite electric charge (conventionally, for many particles, the antiparticles carry a bar above the symbol, e.g. the antiparticle of u is $\bar{u}$). The antiparticles of the charged leptons are often denoted by a change of $-$ to $+$, so the positron e^+ is the antiparticle of the electron e^- etc. The antineutrinos $\bar{\nu}$ differ from the neutrinos ν by a change in helicity.

Hadrons are made from bound states of quarks (which are colour neutral singlets).

i) The *baryons* are formed from bound states of three quarks qqq; antibaryons are formed from bound states of three antiquarks $\bar{q}\bar{q}\bar{q}$

For example, the nucleons are given by

$$\begin{cases} p = uud & : \quad 938 \ Mev \\ n = udd & : \quad 940 \ Mev \end{cases}$$

ii) *Mesons* are formed from bound states of a quark and an antiquark $q\bar{q}$.

For example, the pions are given by

$$\begin{cases} \pi^+ = u\bar{d} & : \quad 140 \ Mev \\ \pi^- = d\bar{u} & : \quad 140 \ Mev \\ \pi^0 = u\bar{u}, d\bar{d} \text{ superposition} & : \quad 135 \ Mev \end{cases}$$

Other particles are made from heavy quarks; such as the strange particles $K^+ = u\bar{s}$ with mass 494 Mev , $\Lambda = uds$ with mass 1115 Mev, and Charmonium $\psi = c\bar{c}$ with mass 3.1 Gev.

The *gauge particles* mediate forces between the hadrons and leptons. They are bosons, with integral spin.

	Mass (GeV)	Interaction
γ (photon)	0	Electromagnetic
W^+	80	Weak
W^-	80	Weak
Z^0	91	Weak
g (gluon)	0	Strong

The gluons are responsible for interquark forces which bind quarks together in nucleons. It is conjectured that a spin 2 gauge boson called the graviton is the mediating particle for gravitational forces, though detecting this is extremely difficult, due to the weakness of gravitational forces compared to other interactions.

1.2 Interactions

There are three types of interaction which are of importance in particle physics: the strong, electromagnetic and weak interactions.

1.2.1 The Strong Interaction

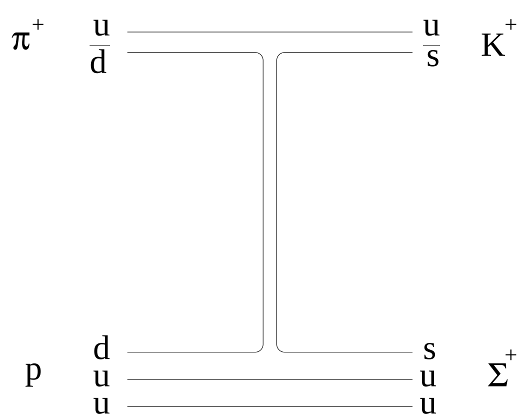
The strong interaction is the strongest interaction.

- Responsible for binding of quarks to form hadrons (electromagnetic effects are much weaker)
- Dominant in scattering processes involving just hadrons. For example, $pp \rightarrow pp$ is an elastic process at low energy; whereas $pp \longrightarrow pp\pi^+\pi^-$ is an inelastic process at higher energy.
- Responsible for binding forces between nucleons p and n, and hence for all nuclear structure.

Properties of the Strong Interaction:

i) The strong interaction preserves quark flavours, although $q\bar{q}$ pairs can be produced and destroyed provided q, $\bar{q}$ are the same flavour.

An example of this is:



The Σ^+ and K^+ particles decay, but not via the strong interaction, because of conservation of strange quarks.

ii) Basic strong forces are "flavour blind". For example, the interquark force between $q\bar{q}$ bound states in the $\psi = c\bar{c}$ (charmonium) and $\Upsilon = b\bar{b}$ (bottomonium) mesons are well-approximated by the potential

$$V \sim \frac{\alpha}{r} + \beta r \tag{1.1}$$

and the differences in energy levels for these mesons is approximately the same.

The binding energy differences can be attributed to the mass difference of the b and c quarks.

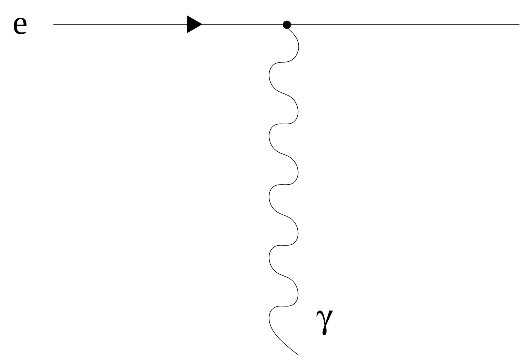
iii) Physics is unchanged if all particles are replaced by antiparticles.

The dynamical theory governing the strong interactions is Quantum Chromodynamics (QCD), which is a gauge theory of quarks and gluons. This is well tested in the perturbative regime; non-perturbative calculations are difficult.

1.2.2 Electromagnetic Interactions

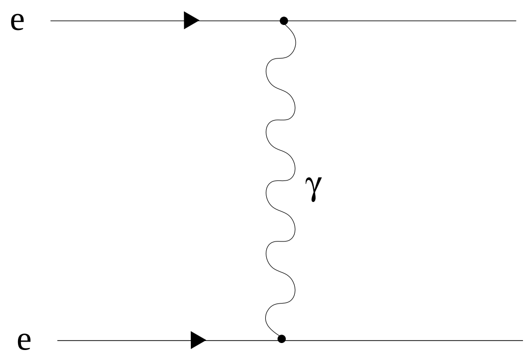
The electromagnetic interactions are weaker than the strong interactions. They occur in the interactions between electrically charged particles, such as charged leptons, mediated by photons.

The simplest electromagnetic process consists of the absorption or emission of a photon by an electron:

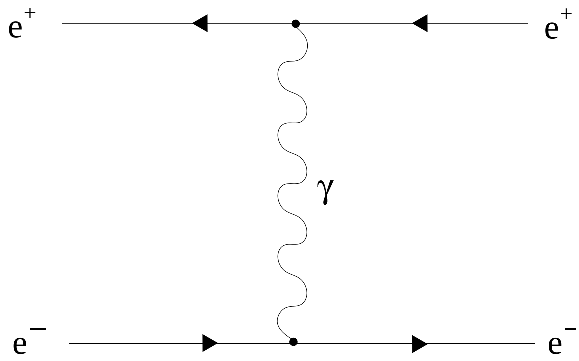


This process cannot occur for a free electron, as it would violate conservation of 4-momentum, rather it involves electrons in atoms, and the 4-momentum of the entire atom and photon are conserved.

Other examples of electromagnetic interactions are electron scattering mediated by photon exchange



and there are also smaller contributions to this process from multi-photon exchanges. Electron-positron interactions are also mediated by electromagnetic interactions



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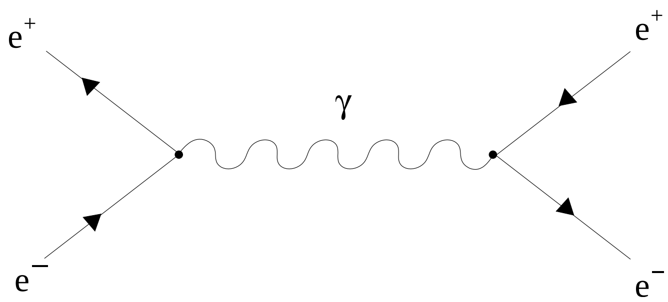
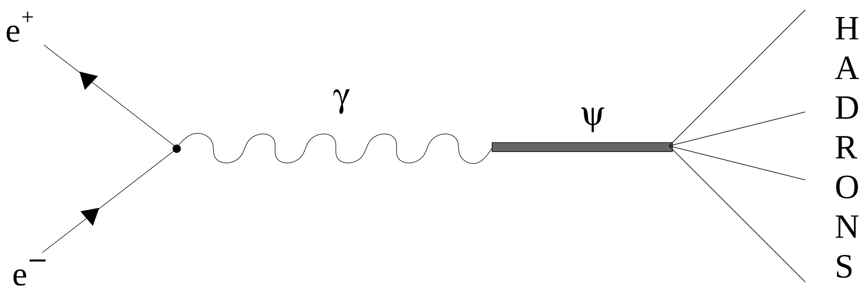


Electron-positron annihilation can also produce particles such as charmonium or bottomonium



The dynamic theory governing electromagnetic interactions is Quantum Electrodynamics (QED), which is very well tested experimentally.

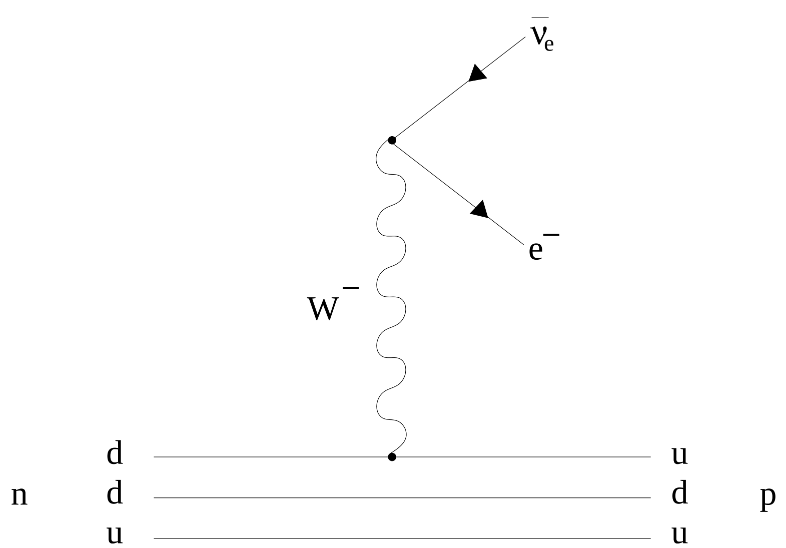
Neutrinos have no electromagnetic or strong interactions.

1.2.3 The weak interaction

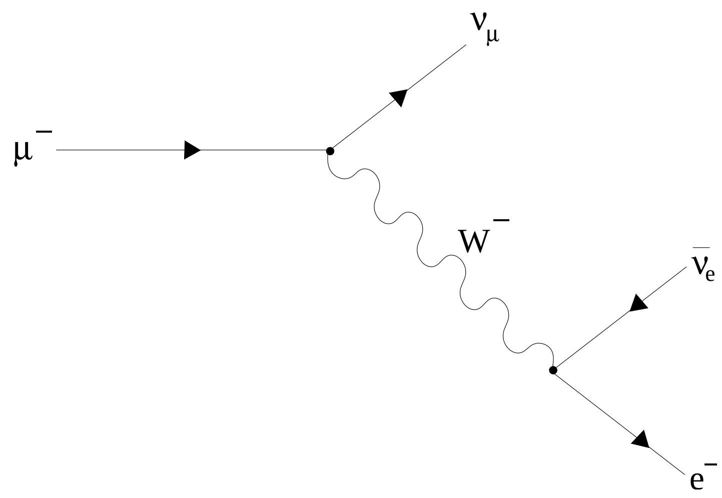
The weak interaction is considerably weaker than both the strong and electromagnetic interactions, they are mediated by the charged and neutral vector bosons $W^{\pm}$ and Z^0 which are very massive and produce only short range interactions. Weak interactions occur between all quarks and leptons, however they are in general negligable when there are strong or electromagnetic interactions present. Only in the absence of strong and electromagnetic interactions is the weak interaction noticable.

Unlike the strong and electromagnetic interactions, weak interactions can involve neutrinos. Weak interactions, unlike strong interactions, can also produce flavour change in quarks and neutrinos.

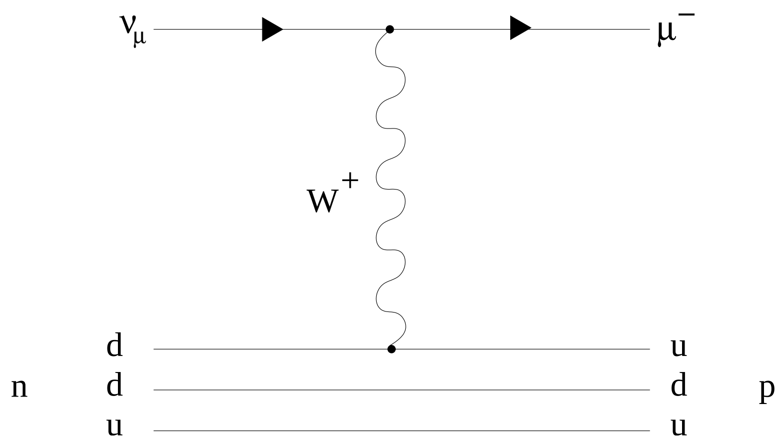
The gauge bosons $W^{\pm}$ carry electric charge and they can change the flavour of quarks. Examples of W-boson mediated weak interactions are $n \longrightarrow p + e^- + \bar{\nu}_e$:



and $\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$:



and $\nu_\mu + n \to \mu^- + p$

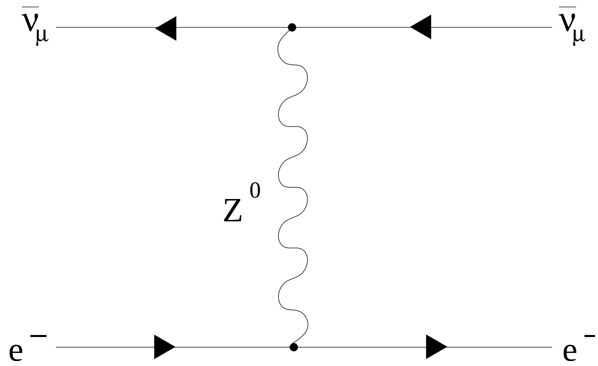


The flavour changes within one family are dominant; e.g.

$$\begin{array}{cc} e^- \leftrightarrow \nu_e, & \mu^- \leftrightarrow \nu_\mu \\ u \leftrightarrow d, & c \leftrightarrow s \end{array} \tag{1.2}$$

whereas changes between families, like $u \leftrightarrow s$ and $u \leftrightarrow b$ are “Cabibbo suppressed”.

The neutral Z^0, like the photon, does not change quark flavour; though unlike the photon, it couples to neutrinos. An example of a Z^0 mediated scattering process is $\bar{\nu}_\mu e^-$ scattering:



In any process in which a photon is exchanged, it is possible to have a Z^0 boson exchange. At low energies, the electromagnetic interaction dominates; however at high energies and momenta, the electromagnetic and weak interactions become comparable. The unified theory of electromagnetic and weak interactions is Weinberg-Salam theory.

1.2.4 Typical Hadron Lifetimes

Typical hadron lifetimes (valid for most decays) via the three interactions are summarized below:

Interaction	Lifetime (s)
Strong	$10^{-22} - 10^{-24}$
Electromagnetic	$10^{-16} - 10^{-21}$
Weak	$10^{-7} - 10^{-13}$

with the notable exceptional case being weak neutron decay, which has average lifetime of $10^3 s$.

1.3 Conserved Quantum Numbers

Given a configuration of particles containing particle P, we define $N(P)$ to denote the number of P-particles in the configuration. We define various quantum numbers associated with leptons and hadrons.

Definition 1. *There are three lepton numbers. The electron, muon and tauon numbers are given by*

$$\begin{aligned} L_e &= N(e^-) - N(e^+) + N(\nu_e) - N(\bar{\nu}_e) \\ L_\mu &= N(\mu^-) - N(\mu^+) + N(\nu_\mu) - N(\bar{\nu}_\mu) \\ L_\tau &= N(\tau^-) - N(\tau^+) + N(\nu_\tau) - N(\bar{\nu}_\tau) \end{aligned} \quad (1.3)$$

In electromagnetic interactions, where there are no neutrinos involved, conservation of L is equivalent to the statement that leptons and anti-leptons can only be created or annihilated in pairs. For weak interactions there are more possibilities, so for example, an election e^- and anti-neutrino $\bar{\nu}_e$ could be created. Lepton numbers are conserved in all interactions.

There are also various quantum numbers associated with baryons.

Definition 2. *The four quark numbers S, C, $\tilde{B}$ and T corresponding to strangeness, charm, bottom and top are defined by*

$$\begin{aligned} S &= -(N(s) - N(\bar{s})) \\ C &= (N(c) - N(\bar{c})) \\ \tilde{B} &= -(N(b) - N(\bar{b})) \\ T &= (N(t) - N(\bar{t})) \end{aligned} \tag{1.4}$$

These quark quantum numbers, together with $N(u) - N(\bar{u})$ and $N(d) - N(\bar{d})$, are conserved in strong and electromagnetic interactions, because in these interactions quarks and antiquarks are only created or annihilated in pairs. The quark quantum numbers are *not* conserved in weak interactions, because it is possible for quark flavours to change.

Definition 3. *The baryon number B is defined by*

$$B = \frac{1}{3}(N(q) - N(\bar{q})) \tag{1.5}$$

where $N(q)$ and $N(\bar{q})$ are the total number of quarks and antiquarks. Baryons therefore have $B = 1$ and antibaryons have $B = -1$; mesons have $B = 0$. B is conserved in all interactions.

Note that one can write

$$B = \frac{1}{3}(N(u) - N(\bar{u}) + N(d) - N(\bar{d}) + C + T - S - \tilde{B}) \tag{1.6}$$

Definition 4. *The quantum number Q is the total electric charge. Q is conserved in all interactions*

In the absence of charged leptons, such as in strong interaction processes, one can write

$$Q = \frac{2}{3}(N(u) - N(\bar{u}) + C + T) - \frac{1}{3}(N(d) - N(\bar{d}) - S - \tilde{B}) \tag{1.7}$$

Hence, for strong interactions, the four quark quantum numbers S, C, $\tilde{B}$, T together with Q and B are sufficient to determine $N(u) - N(\bar{u})$ and $N(d) - N(\bar{d})$.

1.3.1 Angular Momentum and Spin

The *orbital angular momentum* operators L_a acting on wavefunctions are given by

$$L_a = -i\epsilon_{abc}x^b \frac{\partial}{\partial x^c} \tag{1.8}$$

These operators satisfy

$$[L_a, L_b] = i\epsilon_{abc}L_c \tag{1.9}$$

and hence correspond to a representation of $SU(2)$. Particles also carry a *spin angular momentum* $\mathbf{S}$, which commutes with the orbital angular momentum $[\mathbf{L}, \mathbf{S}] = 0$. The *total angular momentum* is defined by $\mathbf{J} = \mathbf{L} + \mathbf{S}$. States $|j, m\rangle$ are labelled by the eigenvalues $\hbar m$ of J_3 and $\hbar^2 j(j+1)$ of $\mathbf{J}^2$.

1.3.2 Isospin

It is observed that the proton and neutron have similar mass, and also that the strong nuclear forces between nucleons are similar. Heisenberg introduced the concept of a $SU(2)$ isospin symmetry to systematize this. Particles are grouped into multiplets of isospin value I (previously called j) and labelled by the weights, which are the eigenvalues of I_3. Originally, this was formulated for nucleons, but later extended to describe all mesons and baryons.

Particles in the same isospin multiplet have the same baryon number, the same content of non-light quarks, the same spin and parity and almost the same mass. Isospin is a conserved quantum number in all known processes involving only strong interactions: it is related to the quark content by

$$I_3 = \frac{1}{2}(N(u) - N(\bar{u}) - (N(d) - N(\bar{d}))) \tag{1.10}$$

Isospin symmetry arises in the quark model because of the very similar properties of the u and d quarks.

Examples:

i) Nucleons have isospin $I = \frac{1}{2}$; the proton has $I_3 = \frac{1}{2}$, and the neutron has $I_3 = -\frac{1}{2}$:

$$\begin{aligned} n &= |\frac{1}{2}, -\frac{1}{2}\rangle \\ p &= |\frac{1}{2}, \frac{1}{2}\rangle \end{aligned} \tag{1.11}$$

ii) The pions have $I = 1$ with

$$\begin{aligned} \pi^- &= |1, -1\rangle \\ \pi^0 &= |1, 0\rangle \\ \pi^+ &= |1, 1\rangle \end{aligned} \tag{1.12}$$

iii) The strange baryons have $I = 0$ and $I = 1$

$$\begin{aligned} \Sigma^- &= |1, -1\rangle \\ \Sigma^0 &= |1, 0\rangle \\ \Sigma^+ &= |1, 1\rangle \end{aligned} \tag{1.13}$$

and

$$\Lambda^0 = |0,0\rangle \tag{1.14}$$

iv) The strange mesons lie in two multiplets of $I = \frac{1}{2}$

$$\begin{aligned} K^0 &= |\frac{1}{2}, -\frac{1}{2}\rangle \\ K^+ &= |\frac{1}{2}, \frac{1}{2}\rangle \end{aligned} \tag{1.15}$$

and

$$\begin{aligned} K^- &= |\frac{1}{2}, -\frac{1}{2}\rangle \\ \bar{K}^0 &= |\frac{1}{2}, \frac{1}{2}\rangle \end{aligned} \tag{1.16}$$

$K^\pm$ are antiparticles with the same mass, but are in different isospin multiplets because of their differing quark content.

v) The light quarks have $I = \frac{1}{2}$

$$\begin{aligned} d &= |\frac{1}{2}, -\frac{1}{2}\rangle \\ u &= |\frac{1}{2}, \frac{1}{2}\rangle \end{aligned} \tag{1.17}$$

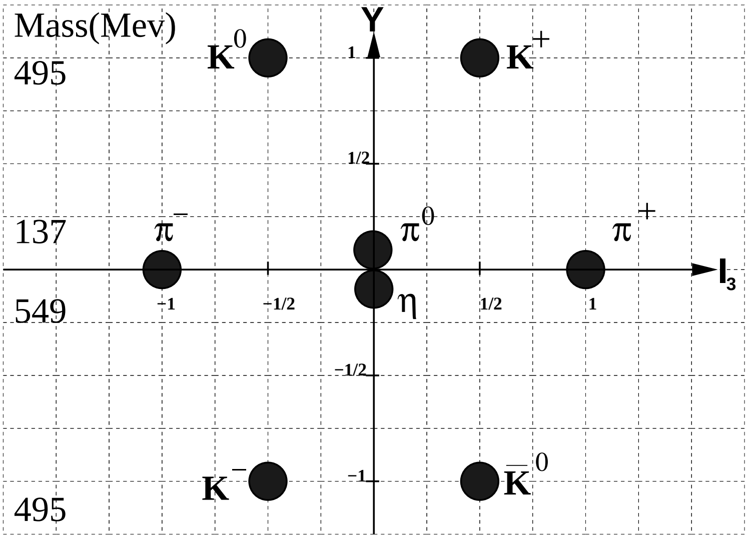
and all other quarks are isospin singlets $I = 0$.

1.4 The Quark Model

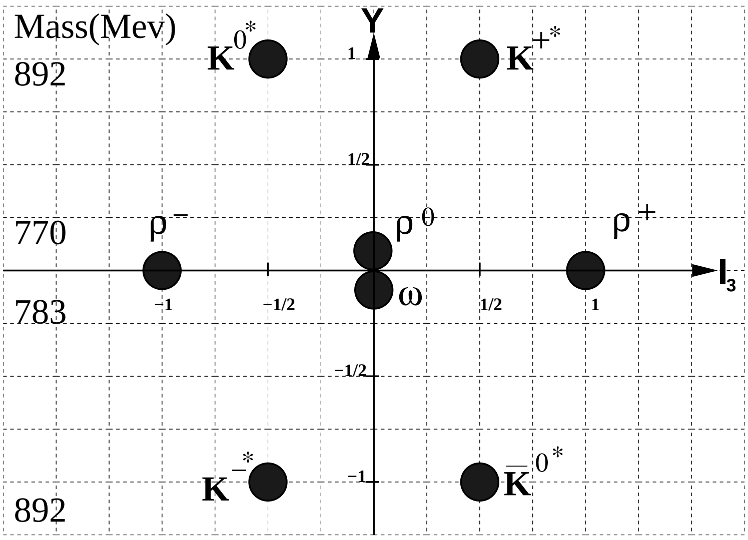
It is convenient to group hadrons into multiplets with the same baryon number and spin. We plot the hypercharge $Y = S + B$ where S is the strangeness and B is the baryon number against the isospin eigenvalue I_3 for these particles.

1.4.1 Meson Multiplets

The pseudoscalar meson octet has baryon number $B = 0$ and spin $J = 0$. The (I_3, Y) diagram is



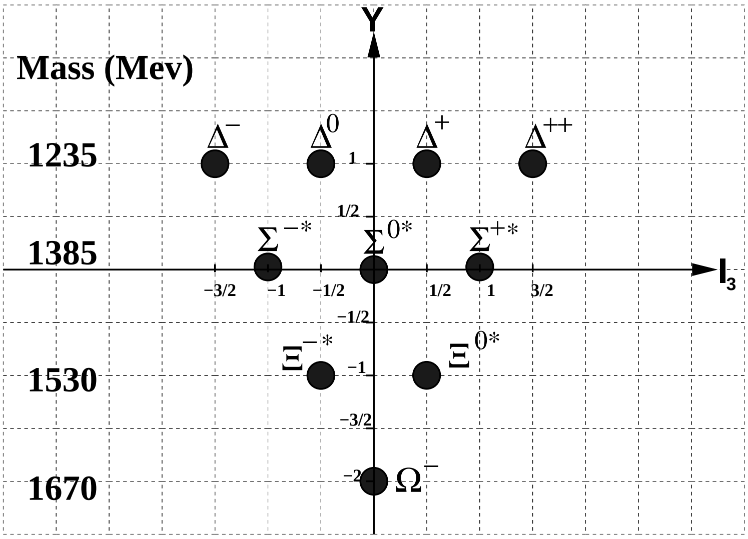
There is also a $J = 0$ meson singlet η'. The vector meson octet has $B = 0$ and $J = 1$. The (I_3, Y) diagram is



There is also a $J = 1$ meson singlet, ϕ.

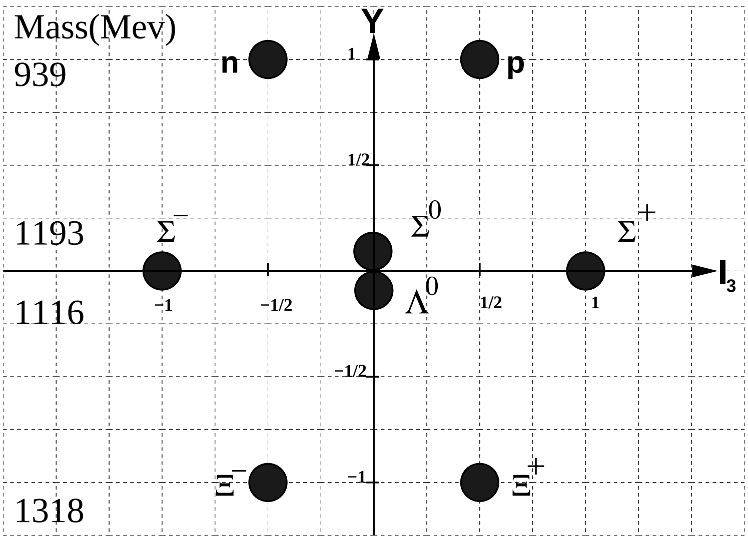
1.4.2 Baryon Multiplets

The baryon decuplet has $B = 1$ and $J = \frac{3}{2}$ with (I_3, Y) diagram



There is also an antibaryon decuplet with $(I_3, Y) \rightarrow -(I_3, Y)$.

The baryon octet has $B = 1$, $J = \frac{1}{2}$ with (I_3, Y) diagram



and there is also a $J = \frac{1}{2}$ baryon singlet Λ^{0*}.

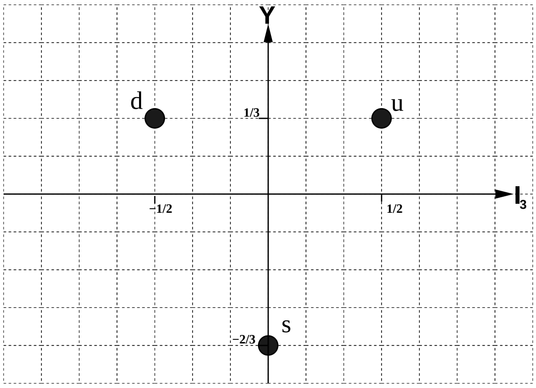
1.4.3 Quarks: Flavour and Colour

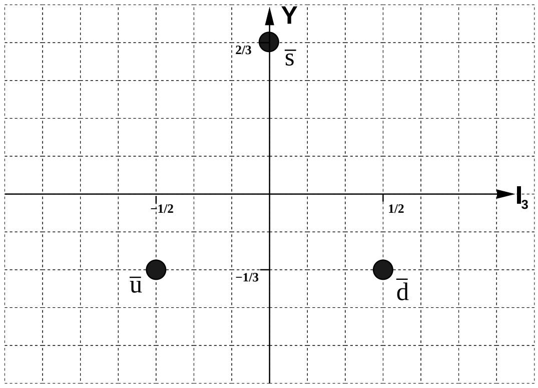
On making the identification $(p, q) = (I_3, \frac{\sqrt{3}}{2}Y)$ the points on the meson and baryon octets and the baryon decuplet can be matched to points on the weight diagrams of the **8** and **10** of $\mathcal{L}(SU(3))$.

Motivated by this, it is consistent to consider the (light) meson states as lying within a $\mathbf{3} \otimes \bar{\mathbf{3}}$; as $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$, the meson octets are taken to correspond to the **8** states, and the meson singlets correspond to the singlet **1** states. The light baryon states lie within a $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3}$; the baryon decuplet corresponds to the **10** in $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$; the baryon octet corresponds to appropriate linear combinations of elements in the **8** irreps, and the baryon singlet corresponds to the **1**.

In the quark model, the mesons and baryons area assumed to be bound states of quarks. The patterns of quantum numbers seen above can be understood as arising from those of quarks. In this model, the fundamental states are quarks, with basis states u (up), d (down) and s (strange). The basis labels u, d, s are referred to as the *flavours* of the quarks. There are also antiquarks with basis $\bar{u}$, $\bar{d}$, $\bar{s}$. Baryons are composed of bound states of three quarks qqq, mesons are composed of bound states of pairs of quarks and antiquarks $q\bar{q}$. The quarks have $J = \frac{1}{2}$ and $B = \frac{1}{3}$ whereas the antiquarks have $J = \frac{1}{2}$ and $B = -\frac{1}{3}$ which is consistent with the values of B and J for the baryons and mesons.

The quark and antiquark flavours can be plotted on the (I_3, Y) plane:





Mesons and baryons are constructed from $q\bar{q}$ and qqq states respectively. But why do qq particles not exist? This problem is resolved using the notion of colour. Consider the Δ^{++} particle in the baryon decuplet. This is a $u \otimes u \otimes u$ state with $J = \frac{3}{2}$. The members of the decuplet are the spin $\frac{3}{2}$ baryons of lowest mass, so we assume that the quarks have vanishing orbital angular momentum. Then the spin $J = \frac{3}{2}$ is obtained by having all the quarks in the spin up state, i.e. $u \uparrow \otimes u \uparrow \otimes u \uparrow$. However, this violates the Pauli exclusion principle. To get round this problem, it is conjectured that quarks possess additional labels other than flavour. In particular, quarks have additional charges called *colour* charges- there are three colour basis states associated with quarks called r (red), g (green) and b (blue). The quark state wave-functions contain colour factors which describes their colour; the colour of antiquark states are the 'opposite' of the corresponding quarks, so that the combination of a quark and the corresponding antiquark is colourless. The colour is independent of the flavour.

These colour charges are also required to remove certain discrepancies (of powers of 3) between experimentally observed processes such as the decay $\pi^0 \rightarrow 2\gamma$ and the cross section ratio between the processes $e^+e^- \rightarrow$ hadrons and $e^+e^- \rightarrow \mu^+\mu^-$ and theoretical predictions. However, although colour plays an important role in these processes, it seems that one cannot measure colour directly experimentally- all known mesons and baryons are $SU(3)$ colour singlets (so colour is confined). This principle excludes the possibility of having qq particles, as there is no singlet state in the $SU(3)$ (colour) tensor product decomposition $\mathbf{3} \otimes \mathbf{3}$, though there is in $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3}$ and $\mathbf{3} \otimes \bar{\mathbf{3}}$. Other products of $\mathbf{3}$ and $\bar{\mathbf{3}}$ can also be ruled out in this fashion.

Nevertheless, the decomposition of $\mathbf{3} \otimes \mathbf{3}$ is useful because it is known that in addition to the u, d and s quark states, there are also c (charmed), t (top) and b (bottom) quark flavours. However, the c, t and b quarks are heavier than the u, d and s quarks, and are unstable- they decay into the lighter quarks. The $SU(3)$ symmetry cannot be meaningfully extended to a naive $SU(6)$ symmetry because of the large mass differences which break the symmetry. In this context, meson states formed from a heavy antiquark and a light quark can only be reliably put into $\mathbf{3}$ multiplets, whereas baryons made from one heavy and two light quarks lie in $\mathbf{3} \otimes \mathbf{3} = 6 \oplus \bar{\mathbf{3}}$ multiplets.