PHYS3051 Content Notes

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1 Week 1

1.2 – The Photon (1900 - 1924)

Electromagnetic radiation is ***quantized***, coming in little packages of energy

$$E = h\nu \tag{1.1}$$

where ν is the frequency of the radiation and $h = 6.626 \times 10^{-27}$ erg.s is Planck's constant.
Photoelectric effect: when an incoming photon hits an electron in metal, giving up its energy of $h\nu$, an excited electron breaks through the metal surface, losing in the process an energy w (the so called *work function* of the material). The electron emerges (free) with an energy of

$$E \leq h\nu - w \tag{1.3}$$

1.4 – Antiparticles (1930 - 1956)

For every kind of particle there must exist a corresponding ***antiparticle***, with the same mass but opposite electric charge. The standard notation for antiparticles is an overbar. For example, p denotes a proton and $\overline{p}$ an antiproton. In some cases, it is customary simply to specify the charge. Most people write e^+ for the positron (not $\overline{e}$) and μ^+ for the antimuon. Some neutral particles are their *own* antiparticles. For example, the photon: $\overline{\gamma} \equiv \gamma$.
The antineutron differs from a neutron only in quantum number. Although the net charge of a neutron is zero, the neutron *does* have a charge structure (positive at the center and near the surface, and negative in between) and a magnetic dipole moment. These have opposite signs for $\overline{n}$.
There is a general principle in particle physics that goes under the name of ***crossing symmetry.*** Suppose that a reaction of the form

$$A + B \to C + D$$

is known to occur. Any of these particles can be 'crossed' over to the other side of the equation, provided it is turned into its antiparticle, and the resulting interaction will also be allowed. For example,

$$A \to \overline{B} + C + D$$
$$A + \overline{C} \to \overline{B} + D$$

In addition, the *reverse* reaction occurs: $C+D \to A+B$, but technically this derives from the principle of *detailed balance* rather than from crossing symmetry. However, there is one important caveat in all this: conservation of energy may veto a reaction that is otherwise permissible. e.g. a minimum kinetic energy may need to occur to make up for some mass difference in the reaction.

2 Week 2

1.6 – Strange Particles (1947-1960)

A new particle, with at least twice the mass of the pion was discovered, called the kaon, K^0. This decays via

$$K^0 \to \pi^+ + \pi^- \tag{1.22}$$

A positively charged kaon was also discovered, with

$$K^+ \to \pi^+ + \pi^+ + \pi^- \tag{1.23}$$

Soon after, the lambda, Λ, was discovered, which decays via

$$\Lambda \to p^+ + \pi^- \tag{1.24}$$

which means that the lambda is substantially heavier than the kaon. The lambda belongs with the proton and neutron in the baryon family.

What stops the proton from spontaneously decaying? A law of *conservation of baryon number* was proposed: assign to all baryons a 'baryon' number $A = +1$, and to the antibaryons $A = -1$ – the total baryon number is conserved in any physical process. Since the proton is the lightest baryon, it has nothing to decay down to (while still maintaining baryon number), and so it remains stable.
Unlike leptons and baryons, there is *no* conservation of mesons. In pion decay ($\pi^- \to \mu^- + \overline{\nu}_\mu$) a meson disappears, and in lambda decay a meson is created.

Strange particles are produced by the strong force (the same that holds atomic nuclei together), but they decay by the weak force (the one that accounts for beta decay and all other neutrino processes). Strange particles are also produced in pairs (so called ***associated production***). Each particle was assigned a new property called *strangeness* that (like charge, lepton number, and baryon number) is conserved in any strong interaction. But, unlike those others, is *not* conserved in a weak interaction. Leptons and photons don't experience strong forces at all, so strangeness does not apply to them.

1.8 – The Quark Model (1964)

The quarks come in three types (or 'flavours'): u (for 'up') quark which carries a charge of $\frac{2}{3}$ and a strangeness of 0; the d ('down') quark which carries a charge of $-\frac{1}{3}$ and $S = 0$; the s ('strange') quark which carries a charge of $-\frac{1}{3}$ and $S = -1$. To each quark (q) there corresponds an antiquark ($\overline{q}$), with the opposite charge and strangeness. There are two ***composition rules***:

1. Every baryon is composed of three quarks (and every antibaryon is composed of three antiquarks).

2. Every meson is composed of a quark and an antiquark.

The Pauli exclusion principle states that no two electrons can carry the same state. It was later realised that the same rule applies to all particles of half-integer spin. In particular, the exclusion principle should apply to quarks, which, as we shall see, must carry spin $\frac{1}{2}$. Now the Δ^{++}, for instance, is supposed to consist of three identical u quarks in the same state - appearing to be inconsistent with the Pauli principle. To avoid this, it was proposed that quarks not only come in three flavours, but each of these also come in three *colours* (red, green, and blue, say). To make a baryon, we simply take one quark of each colour, then the three u's in Δ^{++} are no longer identical.

Redness, blueness, and greenness are simply *labels* used to denote three new properties that, in addition to charge and strangeness, the quarks possess. A *red* quark carries one unit of redness, zero blueness, and zero greenness; its antiparticle carries minus one unit of redness, and so on.
The colour terminology has one especially nice feature: it suggests a delightfully simple characterisation of the particular quark combinations that are found in nature:

All naturally occurring particles are colourless.

That is, *either* the total amount of each colour is zero, *or* all three colours are present in equal amounts. This explains why you can't find isolated quarks, and why you can't make a particle out of two, or four quarks (for example). The only colourless combinations you can make are $q\bar{q}$ (the mesons), qqq (the baryons), and $\overline{qqq}$ (the antibaryons).

1.9 – The November Revolution

A newly discovered ψ meson was an electrically neutral, extremely heavy neutron – more than three times the weight of a proton. This particle has an extraordinarily long lifetime (on the order of 10^{-20}s opposed to 10^{-23}s – $\sim$ 1000 times longer). The ψ is a bound state of a new (fourth) quark, the c (for *charm*) and its antiquark, $\psi = (c\bar{c})$.
Eventually, fifth and sixth quarks were identified (b – bottom; t – top, respectively) along with a new heavy meson (the *upsilon*) and a new lepton (the tau, which has its own neutrino).

1.10 – Intermediate Vector Bosons (1983)

The process of beta decay is actually mediated by some exchange particle (instead of it being from a contact interaction). This mediator became known by the name *intermediate vector boson*. There are in fact *three* intermediate vector bosons, two of them charged ($W^{\pm}$) and one neutral (Z).

1.11 – The Standard Model

In the current view, all matter is made out of three kinds of elementary particles: leptons, quarks, and mediators. There are also antileptons, with all the signs reversed. The

l	Q	L_e	L_μ	L_τ
e	-1	1	0	0
ν_e	0	1	0	0
μ	-1	0	1	0
ν_μ	0	0	1	0
τ	-1	0	0	1
ν_τ	0	0	0	1

Table 1: Lepton Classification

positron, for example, carries a charge of +1 and an electron number -1.
Similarly, there are six 'flavours' of quarks, classified by charge, strangeness (S), charm (C), beauty (B), and truth (T) as well as 'upness', U, and 'downness', D.

q	Q	D	U	S	C	B	T
d	$-1/3$	-1	0	0	0	0	0
u	$2/3$	0	1	0	0	0	0
s	$-1/3$	0	0	-1	0	0	0
c	$2/3$	0	0	0	1	0	0
b	$-1/3$	0	0	0	0	-1	0
t	$2/3$	0	0	0	0	0	1

Table 2: Quark Classification

Again, all signs would be reversed on the table of antiquarks. Meanwhile, each quark and antiquark comes in three colours, so there are 36 of them in all.

Finally, every interaction has its mediator – the photon for the electromagnetic force, two W's and a Z for the weak force, the graviton (presumably) for gravity, and now the ***gluon*** for the strong force (which is exchanged between quarks in a strong process). Gluons carry colour and so should not exist as isolated particles.

3 Week 3

2.1 – The Four Forces

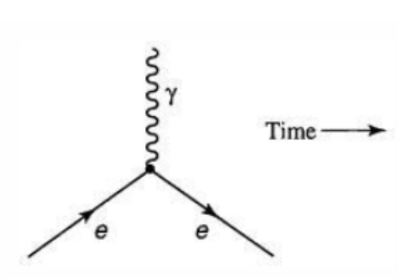
As far as we know, there are just four fundamental forces in nature:

Force	Strength	Theory	Mediator
Strong	10	Chromodynamics	Gluon
Electromagnetic	10^{-2}	Electrodynamics	Photon
Weak	10^{-13}	Flavordynamics	W and Z
Gravitational	10^{-42}	Geometrodynamics	Graviton

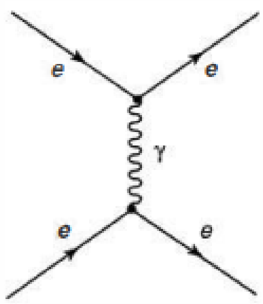
Table 3: The Four Forces

2.2 – Quantum Electrodynamics (QED)

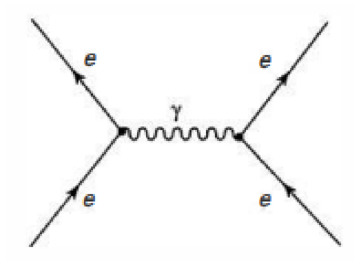
All electromagnetic phenomena are ultimately reducible to the following elementary process



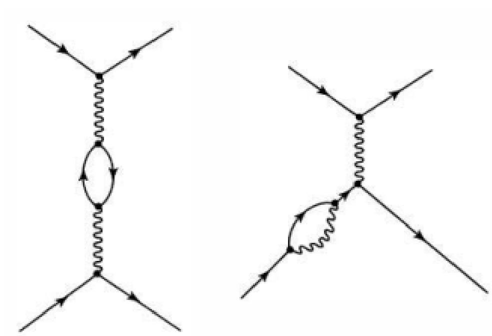
In these figures, time flows horizontally to the right (often represented as time flowing vertically up, too). So, the above diagram reads: a charged particle, e, enters, emits (or absorbs) a photon, γ, and exits.



In the above diagram, two electrons enter, a photon passes between them (it doesn't matter which emits and which absorbs; the diagram represents both orderings), and the two exit. In QED, this process is called ***Moller scattering***; we say that the interaction is mediated by the exchange of a photon.



A particle line running 'backward in time' (an arrow pointing to the left) is interpreted as the corresponding *antiparticle* going forward (the photon is its own antiparticle, hence no arrow is needed). In the above process, an electron and a positron annihilate to form a photon, which in turn produces a new electron-positron pair.

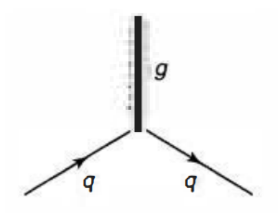


In each of the above figures, two electrons went in and two electrons came out. The 'innards' of the diagram are irrelevant as far as the observed process is concerned. Internal lines (those which begin and end within the diagram) represent particles which are not observed – indeed, that *cannot* be observed without entirely changing the process. We call them ***virtual particles***. Only the *external* lines (those that enter or leave the diagram) represent 'real' (observable) particles. The external lines, then, tell you what physical process is occurring; the internal lines describe the *mechanism* involved.

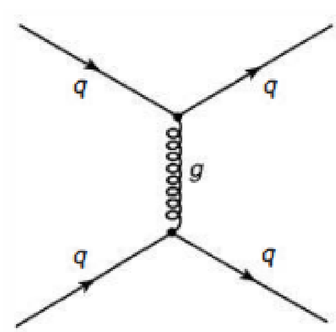
The Feynman rules enforce conservation of energy and momentum at each vertex, and hence for the diagram as a whole. As such, a pair annihilation will always produce *two* photons due to conservation of momentum (as photons have momentum, and the particle and antiparticle pair contact with opposite and equal momenta).

2.3 – Quantum Chromodynamics (QCD)

In chromodynamics, *colour* plays the role of charge, and the fundamental process (analogous to $e \to e + \gamma$) is quark $\to$ quark plus gluon ($q \to q + g$):



As before, we combine two or more such 'primitive vertices' to represent more complicated processes. For example, the force between two quarks (which is responsible in the first instance for binding quarks together to make hadrons) is described in lowest order by the diagram:



We say that the force between two quarks is 'mediated' by the exchange of gluons.

At this level, chromodynamics is similar to electrodynamics. However, there is only one kind of electric charge, but there are *three* kinds of colour. In the fundamental process $q \to q + g$, the colour of the quark (but not its flavour) may change. In this case, the gluon must carry away the difference in colour. Gluons, then, are 'bicoloured', carrying one positive unit of colour (taken from a quark) and one negative unit (where the negative value is the colour given to the quark). Since the gluons themselves carry colour, they couple directly to other gluons, and hence in addition to the fundamental quark-gluon vertx, we also have primitive gluon-gluon vertices.

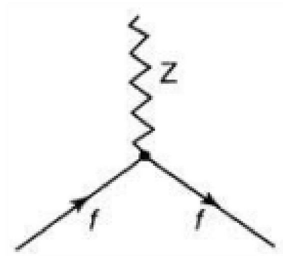
2.4 – Weak Interactions

There is no particular name for the 'stuff' that produces weak forces, in the sense that electric charge produces electromagnetic forces and colour produces strong forces. Some call it

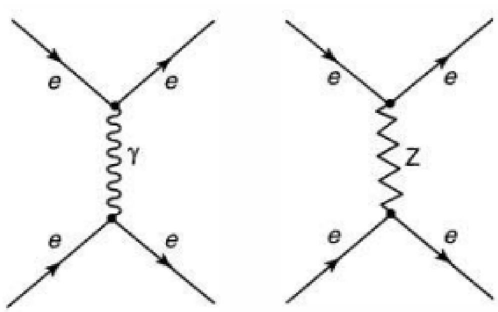
'weak charge', but whatever word you use, all quarks and leptons carry it.
Leptons have no colour (and so don't experience the strong force), neutrinos have no charge (and so don't experience electromagnetic forces), but all of them experience weak interactions. There are two kinds of weak interactions: *charged* (mediated by the Ws) and *neutral* (mediated by the Z).

2.4.1 - Neutral

The fundamental neutral vertex is



where f can be any lepton or quark.
Any process mediated by the photon could also be mediated by the Z - for example, electron-electron scattering:

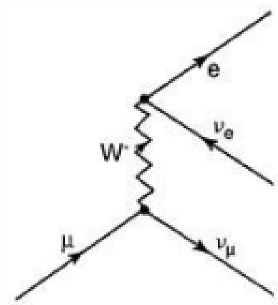


although photon-mediated processes overwhelmingly dominate.

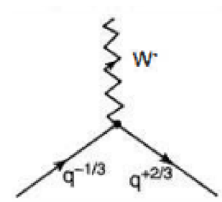
2.4.2 - Charged

The primitive vertices for strong, electromagnetic, and neutral weak interactions all share the feature that the *same* quark or lepton comes out as went in (at least the same flavour) – accompanied, of course, by a gluon, photon, or Z, as the case may be. The charged weak interactions are the only ones that change flavour, and in this sense they are the only ones capable of causing a 'true' decay (as opposed to a mere repackaging of the quarks, or a hidden pair production/annihilation).

2.4.2.1 Leptons
The fundamental charged vertex is described by a negative lepton (it could be e^-, μ^-, or τ^-) converting into the corresponding neutrino, with emission of a W^- (or absorption of a W^+): $l^- \to \nu_l + W^-$.
As always, we combine the primitive vertices to generate more complicated reactions. Since Ws are charged, they must have a direction in their arrows. For example, the decay of a muon $\mu^- \to e^- + \nu_\mu + \overline{\nu_e}$:

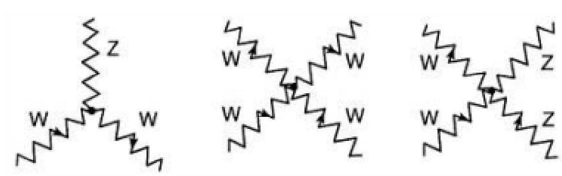


2.4.2.2 Quarks
Notice that the leptonic weak vertices connect members of the *same* generation: e^- converts to ν_e (with an emission of W^-), etc. In this way, the theory enforces the conservation of electron number, muon number, and tau number. It is tempting to suppose that the same rule applies to the quarks, so that the fundamental charged vertex is

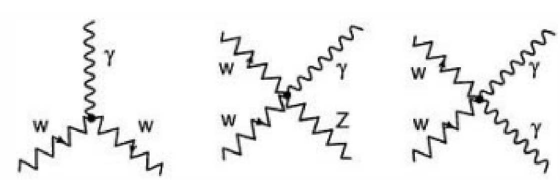


A quark with the charge $-\frac{1}{3}$ converts into the corresponding quark with charge $+\frac{2}{3}$ with the emission of a W^-. The outgoing quark carries the same colour as the ingoing one, but with a different flavour. The far end of the W line can couple to leptons (a 'semileptonic' process), or to other quarks (a purely hadronic process).

2.4.2.3 Weak and Electromagnetic Couplings of W and Z There are also direct couplings of W and Z to one another (just as there are direct gluon-gluon couplings in QCD):



Moreover, because the W is charged, it couples to the photon:



2.5 – Decays and Conservation Laws

One of the most striking general properties of elementary particles is their tendency to disintegrate; we might also call it a universal principle that *every particle decays into lighter* *particles, unless prevented from doing so by some conservation law.* The photon is stable (having zero mass); the electron is stable (it's the lightest charged particle, so conservation of charge prevents decay); the proton is presumably stable (it's the lightest baryon, and the conservation of baryon number saves it) – likewise, conservation of lepton number protects the lightest of the neutrinos. But, *most* particles spontaneously disintegrate – even the neutron (although it is stable in the environment of many atomic nuclei). In practice, our world is populated by these stable particles; more exotic things are created now and then (by collisions), but often don't last long. Each unstable species has a characteristic lifetime of some fraction of a second. In fact, most particles exhibit several decay modes, where some proportion of the same species of particle will decay into one group of products, and another proportion into another group of products – called ***branching ratios***.