Interactions and Fields

In **classical physics**, interaction at a distance is described by a potential. Under the influence of the potential, particles follow smooth, continuous trajectories.

In **quantum mechanics**, the defined trajectory is replaced by a probability distribution, derived from a wave function. The interaction is still considered as a smooth, continuous potential.

Quantum field theory describes interactions at very small distances. The quantum nature of the interaction makes it necessary to abandon the continuous potential model, and we must regard the interaction as being propagated by individual quanta (bosons) which are specific to the type of interaction. (This is known as *second quantisation*.)

In modern field theories, we have the fundamental forces transmitted by the exchange of bosons (particles of spin 0, 1, 2, …). Two basic types of fundamental field can occur – ones in which the fermions act as sources of the field and the bosons act simply as propagators, and ones in which both the fermions and the bosons themselves act as sources. An example of the former is electromagnetism, where electric charge (on an electron for example) is a source and the boson is the photon, which is neutral.

The four fundamental forces are electromagnetism, the weak force responsible for nuclear beta decay, the strong (nuclear) force and gravity. Their properties are given in the table below.

Interaction	Source	Field quanta			Strength
		Particle	spin	mass	
Strong	"colour" (carried by quarks and gluons)	gluon g	1	0	~1 at large distance <1 at small distance
Electromagnetism	charge (carried by e,μ,τ and quarks)	photon γ	1	0	$\sim 10^{-2}$
Weak	all leptons and quarks	$W^{\pm}$,Z	1	80-90 GeV/c^2	$\sim 10^{-13}$ @10^{-15} m $\sim 10^{-2}$ @10^{-18} m
Gravity	energy density	Graviton G	2	0	$\sim 10^{-38}$

Further details of these interactions are given overleaf.

Gravity, of great importance between macroscopic bodies (like us and the earth) is too weak to play an important rôle between fundamental particles. We will only make one remark – that the spin of the graviton (2) is related to the fact that there is only positive mass, so dipole radiation is not a possibility.

As we will see shortly, the short range of the weak interaction (and hence its name) is related to the mass of its bosons. (At very short distances, it is no weaker than electromagnetism.) Note that all fermions experience the weak interaction.

Electromagnetism is the everyday force responsible for chemistry, solid state physics, friction and the stability of atomic matter in general.

The reason for the "strong charge" being given the name of "colour" will be revealed later - it has nothing to do with the normal colour of an object! The strong interaction was originally postulated to bind protons (and neutrons) together in nuclei against the large electromagnetic repulsion. We now know that this is a second-order effect similar to the Van der Waal's (electromagnetic) force which binds neutral covalent molecules in solids. The proton and neutron (and all hadrons) are "colourless" or colour neutral.

In this course, we will examine three of the forces (excluding gravity) in some detail. However, we will first look at the general properties of interactions mediated by the exchange of bosons, before returning to each type of interaction in turn.

We can get a qualitative feel for the spatial dependence of a force mediated by boson exchange. Consider the interaction between two charges a distance r apart. One charge emits *virtual photons*, which are absorbed by the other. The photon is virtual as it can only exist within the freedom of the uncertainty principle, so the allowed momentum q is related to r by $q\,r \sim \hbar$. The transfer of this momentum takes a time $t = r/c$. So the resulting force is given by

$$\frac{\mathrm{d}q}{\mathrm{d}t} \sim \frac{q}{t} \sim \frac{\hbar c}{r^2} \propto \frac{1}{r^2}\,.$$

If the number of photons emitted and absorbed per unit time is proportional to the product of the two charges, we have a simple rationale for Coulomb's law.

Feynman Diagrams

At high energies, an interaction is dominated by the exchange of a single quantum. Fermion-fermion scattering can then be represented diagrammatically as shown in figure 4a. This is not just a pictorial representation of the process – these diagrams can be used as precise calculating tools for scattering amplitudes when specific rules are applied to each line and vertex. They are then known as Feynman Diagrams.

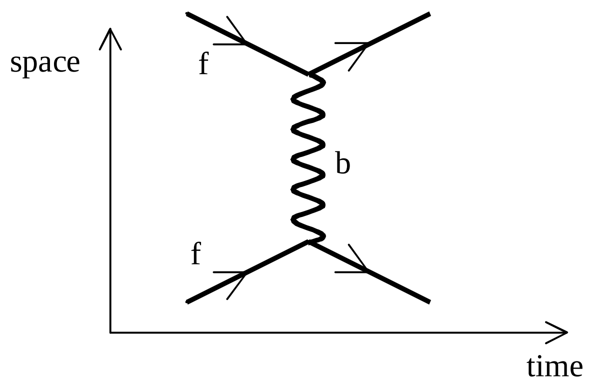

Fig. 4a Fermion-fermion scattering.

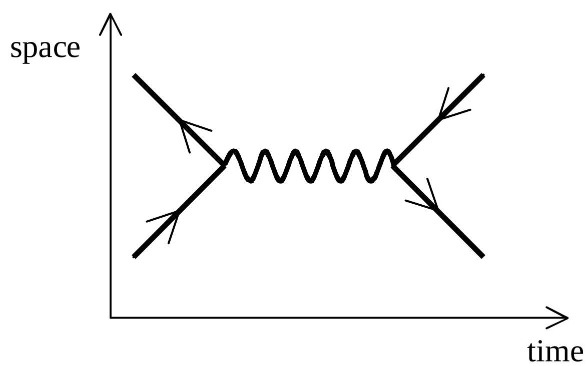

Fig. 4b Fermion-antifermion annihilation.

These diagrams have special space-time properties. If twisted or rotated they reveal intimately related processes, as shown in figure 4b. In this case, we must interpret a "fermion going backwards in time" as a normal antifermion. This diagram therefore shows a fermion-antifermion pair annihilating to produce a (virtual) boson, which then materialises as a new fermion-antifermion pair.