Demonstrations:
- cloud chamber

Text: Mod. Phys. 5.A, 5.B, 5.C, 5.D
Problems: 3, 4, 10, 11, 13 from Ch. 5

What's important:
- contributions of interactions to scattering and decay processes
- conservation laws
- quarks and gluons
- bosons as carriers of force

Interactions in Reactions and Decays

How do the four fundamental forces - strong, electromagnetic, weak and gravitational influence decays or reactions? Consider the scattering process of a pion against a proton:

$$\pi^+ + p \rightarrow \pi^+ + p. \tag{1}$$

The interactions involved in this scattering process are:
(i) gravity, since the particles each have mass
(ii) weak
(iii) electromagnetic, since they are charged
(iv) strong, since they are hadrons

All four interactions are present, but the strong interaction dominates. Hence, the cross section for reaction (1) is in the 10^{-30} m^2 range.

Now, suppose that the pion is replaced by an electron e^-:

$$e^- + p \rightarrow e^- + p. \tag{2}$$

An electron is a lepton (no strong interactions), so the contributing interactions are:
(i) gravity
(ii) weak
(iii) electromagnetic.

The electromagnetic interaction dominates reaction (2) and the cross section for (2) is orders of magnitude less than the cross section for (1), say 10^{-36} m^2.

The same situation applies if the electron is replaced by a photon γ

$$\gamma + p \rightarrow \gamma + p. \tag{3}$$

Even though the photon does not carry charge, it is an electromagnetic wave and it interacts with particles that are charged or have an internal distribution of charge.

Finally, consider the scattering of a neutrino ν by a proton:

$$\nu + p \rightarrow \nu + p. \tag{4}$$

The neutrino interacts only by:
(i) gravity
(ii) weak interaction.
Therefore reaction (4) is dominated by the weak interaction, and the cross section is very small, say 10^{-42} m^2.

A summary of the "rules of thumb" which are contained in the above examples, and apply to both reactions and decays, are:

1. A reaction or decay is dominated by the strongest interaction that is common to all of the particles.

2. If a photon is present in a reaction, then the strong interaction cannot dominate. The dominant interaction is electromagnetic or weak.

3. If a neutrino is present, then neither the strong nor electromagnetic interactions can dominate. The dominant interaction is the weak interaction.

Rules 1 - 3 also apply to decays. Suppose there are competing reactions that can take place in a decay. For example, the decay of the rho meson can occur via both

$$\rho \rightarrow \pi + \pi \tag{5}$$

$$\rho \rightarrow \gamma + \gamma \tag{6}$$

Using Rules 1 - 3, we would argue that (5) is dominated by the strong interaction and (6) is dominated by the electromagnetic interaction. In Nature, both of these decays occur, but it is decay (5) that occurs a thousand times more frequently than (6), because (5) is a strong interaction decay.

Conservation Laws

When particles interact, their energy and momentum can change, as well as their quantum numbers. If a **quantity does not change** during a reaction, then the quantity is said to be **conserved**; otherwise, the quantity is not conserved. The best-known conservation laws in kinematics are conservation of energy and of momentum.

In the simple scattering process

$$A + B \rightarrow C + D \qquad (7)$$

the quantum numbers of the group (A+B or C+D) are just equal to the algebraic sum of the individual particle quantum numbers (except for spin). For example,

$e^- + e^-$:
$\mathbf{Q} = -1 + (-1) = -2$ $\mathbf{L}_e = 1 + 1 = 2$ $\mathbf{B} = 0 + 0 = 0$

$e^+ + e^-$:
$\mathbf{Q} = 1 + (-1) = 0$ $\mathbf{L}_e = -1 + 1 = 0$ $\mathbf{B} = 0 + 0 = 0$

where **Q** is quoted in units of the elementary charge *e*.

Experimentally, electric charge is conserved to high accuracy: at least 1 part in 10^{24}! Applied to reaction (7), conservation of charge reads

$$\mathbf{Q}_A + \mathbf{Q}_B = \mathbf{Q}_C + \mathbf{Q}_D.$$

which is an additive conservation law: it is the **sum** of the quantities that is conserved (like conservation of energy). Lepton number and baryon number appear to be similarly conserved.

Example

Apply conservation laws to neutron decay n → p + e^- + anti-ν_e.

Solution:
Initial state: $\mathbf{Q} = 0$ $\mathbf{B} = +1$ $\mathbf{L}_e = 0$
Final state: $\mathbf{Q} = +1 + (-1) + 0 = 0$
$\mathbf{B} = +1 + 0 + 0 = +1$
$\mathbf{L}_e = 0 + 1 + (-1) = 0.$

One can see that **Q**, **B** and $\mathbf{L}_e$ are conserved. Recall that ν_e is distinct from anti-ν_e, which would be generated in the decay of an anti-neutron: anti-n → anti-p + e^+ + ν_e.

In the example, baryons decay into other baryons. But the proton is the lightest baryon, although there are non-baryons into which it could decay. For example:

$$p \rightarrow \pi^o + e^+.$$

This decay has
Initial state: **Q** = +1 **B** = +1 $\mathbf{L}_e$ = 0
Final state: **Q** = 0 + 1 = 1 **B** = 0 + 0 = 0 $\mathbf{L}_e$ = 0 + (-1) = -1.
The only quantities that are violated by this decay are **B** and $\mathbf{L}_e$. Experimentally, a proton has never been observed to decay, from which it has been deduced that the proton lifetime is at least 10^{31} years, far longer than the age of the universe. We conclude that violations of baryon number and lepton number conservation occur only rarely, if ever.

Quarks and Gluons

Hadrons and leptons are spoken of as being elementary particles. But there is considerable evidence from scattering experiments that hadrons have constituents, they appear to be composite systems. The constituents of hadrons are called **quarks**, and the gauge particles that carry the strong interaction between the quarks are called **gluons**. No free quarks and gluons have been isolated in experiments.

There are at least **six flavours** (or different types) of quarks:

Quark		**Q** (e)	**J**	**B**	$\mathbf{L}_e$
name	symbol				
up	*u*	+2/3	1/2	1/3	0
down	*d*	-1/3	1/2	1/3	0
strange	*s*	-1/3	1/2	1/3	0
charm	*c*	+2/3	1/2	1/3	0
bottom	*b*	-1/3	1/2	1/3	0
top	*t*	+2/3	1/2	1/3	0
anti-up	anti-*u*	-2/3	1/2	-1/3	0
anti-down	anti-*d*	+1/3	1/2	-1/3	0
anti-strange	anti-*s*	+1/3	1/2	-1/3	0
anti-charm	anti-*c*	-2/3	1/2	-1/3	0
anti-bottom	anti-*b*	+1/3	1/2	-1/3	0
anti-top	anti-*t*	-2/3	1/2	-1/3	0

While the absolute quark masses have not been determined, the relative masses appear to be ordered $u < d < s < c < b < t$. For example, the top quark has an apparent mass of approximately 190 proton masses, where the proton is made from *u* and *d* quarks.

Note: Each of the *s*, *c*, *b* and *t* quarks carries a unique quantum number (strangeness, charm, beauty and truth respectively). The quarks have spin $J = 1/2$ and are therefore **fermions**.

The quark model proposes that there are three quarks in a baryon and a quark/anti-quark pair in a meson. Some examples

p → (*uud*)
Q = +2/3 + 2/3 + (-1/3) = +1 **B** = 1/3 + 1/3 + 1/3 = 1
$\mathbf{L}_e$ = 0 + 0 + 0 = 0

n → (*udd*)
Q = +2/3 + (-1/3) + (-1/3) = 0 **B** = 1/3 + 1/3 + 1/3 = 1
$\mathbf{L}_e$ = 0 + 0 + 0 = 0.

π^+ → (*u*, anti-*d*)
Q = +2/3 + 1/3 = +1 **B** = 1/3 + (-1/3) = 0
$\mathbf{L}_e$ = 0 + 0 = 0

Addition of the spin quantum number **J** has not been shown in the examples above because: (i) spin is a vector, not a scalar like charge and (ii) the spin angular momentum of quarks can add with the orbital angular momentum of their relative motion. This gives rise to families of particles with the same quark content, but different relative motion. For example: proton (*uud*), N(1440) (*uud*).....

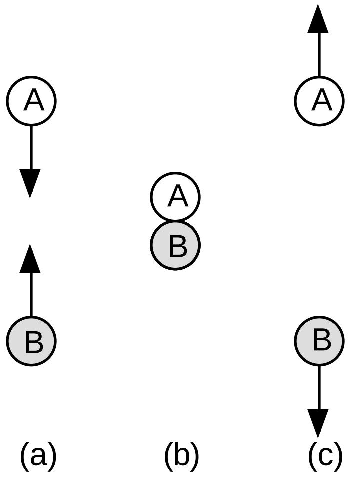
Now, because the proton and neutron have such a small mass difference, then we would expect the up and down quarks to be nearly equal in mass. So the sequence (*uuu*), (*uud*), (*udd*) and (*ddd*) should be similar in mass if the quarks all have similar motion with respect to each other. In fact, there is a family of four particles labelled Δ(1232) that have similar masses and exactly the charge assignments expected for this sequence: Δ^{++}, Δ^{+}, Δ^{o} and Δ^{-}. The Δ^{++} has quark content (*uuu*) with all of the quark quantum numbers, as we have defined them so far, identical. Similarly, the Δ^{-} has (*ddd*). This is a *major* problem. The quarks are fermions, and no two fermions in a group are allowed to have the same quantum numbers!

The existence of the Δ^{++} and Δ^{-} indicate that there must be another quantum number associated with quarks: **colour**. Each flavour of quark (*u*, *d*, *s*, *c*....) comes in three colours: red, green, and blue is the standard choice. In the Δ^{++}, one of the quarks is red, one is green and one is blue. The physical consequences of the existence of the colour quantum number have been verified experimentally.

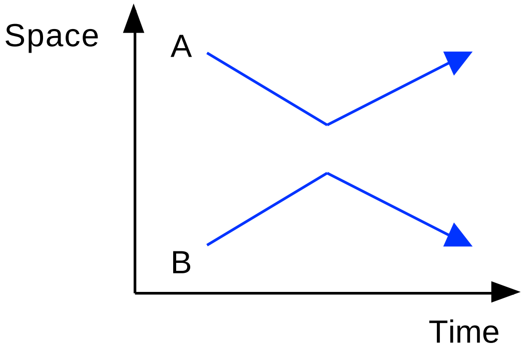
In any given hadron, colour is exchanged among the quarks so that equal amounts of each colour are present. The colour is carried between the quarks by **gluons**, which are massless, neutral particles with **J** = 1. The gluons are the gauge bosons of the interaction between quarks, like the photon is the gauge particle of electromagnetism. The theory of quarks and gluons is referred to as **quantum chromodynamics** or **QCD** (where the origin of the "chromo" should be obvious).

Bosons as carriers of force

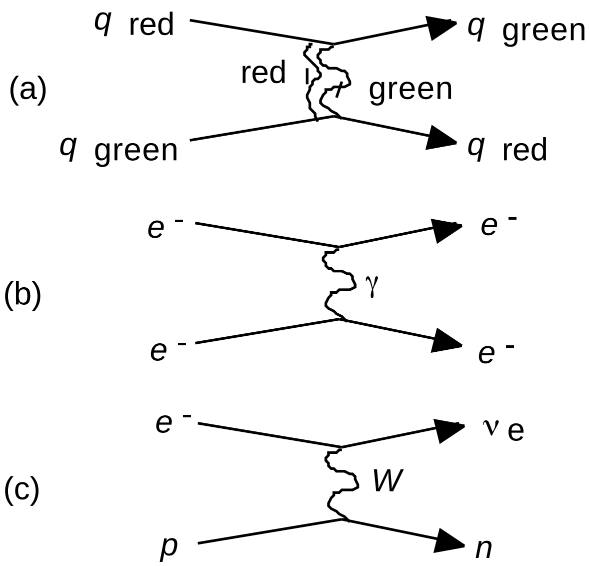
In the macroscopic world, we are used to the idea of "action at a distance": we do not think of gravity or electrostatic interactions as needing a material or mechanical contact. However, on microscopic length scales, it appears that the forces between particles are mediated by the **exchange** of other particles. To visualise particle exchange, consider the motion of two identical hard spheres hitting each other head on: long before the collision (a), at the collision point (b) and long after the collision (c).



A space-time diagram provides a better representation of the time evolution of the collision. The vertical axis is the spatial position of the particle centres, while horizontal axis is the elapsed time. In the figure below, the distance of closest approach of the paths is equal to the diameter of the hard spheres.



In the particle exchange model of interactions, the gap between the paths in the figure is filled by the paths of other particles being exhanged between the scattering pair. For example, the electromagnetic force is thought to be carried or **mediated** by the exchange of photons. While the diagrams show only a single particle exchange during the collision, in practice there are an infinite number of particle exchanges, some of which have more effect than others.



The particles that are thought to mediate the interactions are:
(a) gluons (strong)
(b) photons (electromagnetic)
(c) W^+, W^- and Z^o bosons (weak).
The gluons and photons are massless, while the W and Z particles are far more massive than protons.

Shown in figure (a) are two quarks of unspecified flavour: the upper quark has colour red (**R**) while the lower quark has colour green (**G**). Under gluon exchange, the quark flavours (i.e., *u*, *d*, *s*...) don't exchange but the colours do, the gluon carries **R** in a downward direction and **G** in an upward direction. Gluons don't have a single colour (**R**, **G**, **B**) like quarks, but are characterized by two colours: (anti-**R**, **R**), (anti-**G**, **G**), (anti-**B**, **B**), (anti-**R**, **G**), (anti-**G**, **R**), (anti-**R**, **B**), (anti-**B**, **R**), (anti-**G**, **B**) and (anti-**B**, **G**). We use the antiparticle notation [e.g. (anti-**R**, **B**)] to indicate that the gluon carries one colour in one direction (e.g. **R**) and another in the opposite direction (e.g. **B**). Now it turns out for mathematical reasons that (anti-**R**, **R**), (anti-**G**, **G**) and (anti-**B**, **B**), which carry the same colour in both directions, can be combined to give only two gluons, so that the total number of gluons is actually 8.

The particle-exchange model for the electromagnetic interaction has been very thoroughly tested. The particle exchange model for the weak interaction passes all tests that have been made. In fact, the masses and other properties of the *W* and *Z* were predicted (correctly) by the exchange model years before the *W* and *Z* were observed experimentally.

The gluon-exchange model for strong interactions is more difficult to test. Data on "electron-quark" or "gluon-quark" scattering must be extracted from electron-hadron or hadron-hadron scattering, which is not a trivial task. Currently, the gluon-exchange model is the only one which makes even limited predictions for the strong interactions.

Lastly, there are models for gravity based on particle exchange, but they have internal self-consistency problems. The models propose the existence of a particle called a **graviton**, whose characteristics vary with the model. Because of the small cross section for the interaction of gravitons with matter, gravitons are very difficult to measure, and no convincing evidence for freely propagating gravitons has been found yet.

One note of caution. Results from "classical" studies of electricity and gravity such as Coulomb's law and Newton's law of universal gravitation do not apply under all conditions, particularly at extremely short distances. However, the force equations of the particle exchange models *do* look like the classical results as long as the distances between the interacting particles is large. So the classical results remain excellent approximations that we can use without worry in our everyday world.