CHAPTER 5

INTERACTIONS II

5.A Interactions in Reactions and Decays

In Chapter 2, we discuss the various fundamental forces - strong, electromagnetic, weak and gravitational - by which particles can interact with each other. How do these interactions influence decays or reactions? Consider the scattering process of a pion against a proton:

$$\pi^+ + p \rightarrow \pi^+ + p. \tag{5.1}$$

The initial "state" of the system consists of two hadrons, a pion and a proton. The final state also consists of the same two hadrons, although their momentum has probably been changed by the scattering process. What interactions are involved in the scattering process? Because the particles each have mass, then they can interact via gravity. As hadrons, they may also interact via the weak, electromagnetic and strong interactions. In fact, all of the particles that we see in reaction (5.1) are charged hadrons, so we conclude that *all* interactions may be present. However, it is the strong interaction that dominates over the others, so the cross section for the reaction is a typical strong interaction cross section in the 10^{-29} m^2 range.

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

$$e^- + p \rightarrow e^- + p. \tag{5.2}$$

An electron is a lepton, so it has no strong interactions. But both the electron and the proton carry charge, so they can interact via the electromagnetic interaction (in addition to the weak interaction and gravity). The dominant interaction in reaction (5.2) is then the electromagnetic interaction. The cross section for reaction (5.2) is orders of magnitude less than the cross section for (5.1). The same situation applies if the electron is replaced by a photon γ

$$\gamma + p \rightarrow \gamma + p. \tag{5.3}$$

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:

$$\nu + p \rightarrow \nu + p. \tag{5.4}$$

The neutrino interacts only by the weak interaction and gravity. Hence, we conclude that reaction (5.4) is dominated by the weak interaction. Just because there is a hadron present in reactions (5.2) to (5.4) does not mean that the reaction is dominated by the strong interaction. All of the particles present in a reaction have to be hadrons for the reaction to be dominated by the strong interaction.

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 tell us how to determine which interaction dominates a process when we know both the initial and final particles in the process. Suppose that the final state is not specified or that there are competing reactions that can take place. For example, one of the decays of the rho meson is decay into two pions

$$\rho \rightarrow \pi + \pi. \tag{5.5}$$

But the ρ can also decay into a pion and a gamma ray

$$\rho \rightarrow \pi + \gamma. \qquad (5.6)$$

Using Rules 1 - 3, we would argue that (5.5) is dominated by the strong interaction and (5.6) is dominated by the electromagnetic interaction. In Nature, both of these reactions occur, but it is reaction (5.5) that occurs far more frequently since it is a strong interaction decay. Experimentally, decay (5.5) occurs a thousand times more often than decay (5.6).

Example 5.1: *State which interaction dominates the following reactions and decays:*

Using rules 1 - 3 from above:

$p + n \rightarrow p + n$	strong
$\gamma + p \rightarrow \pi^o + p$	electromagnetic
$\nu + p \rightarrow \nu + p$	weak
$\nu + e^- \rightarrow \nu + e^-$	weak
$\gamma + e^- \rightarrow \gamma + e^-$	electromagnetic
p + anti-$p \rightarrow \gamma + \gamma$	electromagnetic
$\rho \rightarrow \pi + \pi$	strong
$\pi^o \rightarrow \gamma + \gamma$	electromagnetic (even though π^o is neutral)
$\mu \rightarrow \nu$ + anti-$\nu + e$	weak

5.B Conservation Laws

When particles interact, either in a scattering process or in a decay, they can exchange energy and momentum. Their quantum numbers can change as well and there are experimentally-determined rules for what happens to certain quantities during an interaction. If a quantity does not change during a reaction, then the quantity is said to be *conserved*; otherwise, the quantity is not conserved. To further complicate things, there are quantities that are conserved by some interactions but not by others. The best-known conservation laws in kinematics are *conservation of energy* and *conservation of momentum*, as introduced in Chapter 4.

Suppose we have a simple scattering process

$$A + B \rightarrow C + D \tag{5.7}$$

where A, B, C and D are labels representing particles, nuclei or whatever. What are the quantum numbers of a group of particles, such as the pair of particles $A + B$? With the exception of spin, the quantum numbers of the group are just equal to the algebraic sum of the individual particle quantum numbers. For example,

$e^- + e^-$:

$$Q = -1 + (-1) = -2 \quad L_e = 1 + 1 = 2 \quad B = 0 + 0 = 0 \tag{5.8}$$

$e^+ + e^-$:

$$Q = 1 + (-1) = 0 \quad L_e = -1 + 1 = 0 \quad B = 0 + 0 = 0 \tag{5.9}$$

π^+ + anti-p:

$$Q = 1 + (-1) = 0 \quad L_e = 0 + 0 = 0 \quad B = 0 + (-1) = -1 \tag{5.10}$$

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

Electric charge is conserved to high accuracy; experimentally it is conserved to at least 1 part in 10^{24}! Applied to reaction (5.7), conservation of charge reads

$$Q_A + Q_B = Q_C + Q_D. \tag{5.11}$$

The conservation law expressed in equation (5.11) is an additive conservation law: it is the *sum* of the quantities that is conserved, just like conservation of energy in Eq. (4.9).

What about quantum numbers like L_e and B? The evidence for baryon number conservation comes from both decay and scattering processes. It is observed experimentally that the baryon number sum does not change during a reaction

$$B_A + B_B = B_C + B_D \tag{5.12}$$

or during a decay. The same is true for lepton number.

Example 5.2: *Apply baryon and lepton number conservation to neutron decay* $n \rightarrow p + e^- +$ anti-ν_e.

Substituting known quantum numbers:

Initial state: $Q = 0$ $B = +1$ $L_e = 0$

Final state: $Q = +1 + (-1) + 0 = 0$
$B = +1 + 0 + 0 = +1$
$L_e = 0 + 1 + (-1) = 0$.

The summed quantum numbers in the initial state and final state are equal.

One aspect of baryon number conservation evident in Example 5.2 is that baryons decay into other baryons. But what about the proton? It is the lightest baryon, so there are no lighter baryons into which it can decay. But there are non-baryons into which it could decay. Consider the decay of a proton into a pion and an antielectron (positron):

$$p \rightarrow \pi^o + e^+. \tag{5.13}$$

This decay has

$$Q = +1 \qquad B = +1 \qquad L_e = 0 \tag{5.14}$$

in the initial state and

$$Q = 0 + 1 = 1 \qquad B = 0 + 0 = 0 \qquad L_e = 0 + (-1) = -1 \tag{5.15}$$

in the final state. The only quantities that are violated by this decay are B and L_e. Energy, momentum, spin and charge all are conserved. 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 conservation occur only rarely, if ever. Similar conclusions can be drawn about lepton number conservation.

Although we have not demonstrated it, the quantities Q, B and L_e are conserved by all interactions, not just strong or electromagnetic interactions. But we should always bear in mind that the conservation laws are experimentally based, even though they have strong theoretical implications. Right now, conservation of B and L_e are receiving a lot of experimental scrutiny, since their *non-conservation* is required by most theoretical models trying to explain why our current universe is mainly matter and not a mixture of matter and antimatter.

5.C 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 just like a nucleus is a composite system composed of nucleons. 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 or gluons have ever been observed, so their masses are unknown.

There are at least six different types or *flavours* of quarks. Each quark has baryon number of 1/3, and an electric charge that is smaller in absolute magnitude than e. As of 1977, there was solid evidence for five flavours: up (u), down (d), strange (s), charmed (c) and bottom (b). In March of 1995, two experimental groups announced independent evidence for a sixth or *top* quark (t). The experiments took about a decade of painstaking work; in one experiment, only 40 reactions out of a total sample of 6,000,000,000,000 (yes, that's six trillion) showed reasonably clean evidence for the production of a top quark.

While the absolute quark masses have not been determined, the relative masses appear to be ordered $u < d < s < c < b < t$. For example, protons and neutrons consist of u-quarks and d-quarks. In comparison, the lightest particle containing a b-quark has a mass that is more than five times the proton mass, indicating that the b-quark has a relatively large mass compared to the u-quark. The top quark has an apparent mass of approximately 190 proton masses.

Table 5.1. Some quantum numbers of the six quarks and their antiquarks. The quarks are arranged in order of increasing effective mass.

Quark name	Quark symbol	Q (e)	J	B	L_e
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

Each of the s, c, b and t quarks carries a unique quantum number (strangeness, charm, beauty and truth respectively) that is additive and conserved by strong and electromagnetic (but not weak) interactions. We will not pursue the properties of these other hadronic quantum numbers (strangeness, charm...) in these lectures. Like the proton, neutron, electron and neutrino, the quarks have spin $J = 1/2$ and are therefore *fermions*. Some quark properties are summarized in Table 5.1.

The quark model proposes that there are three quarks in a baryon and a quark/anti-quark pair in a meson. The quark content of protons and neutrons would be

$$\mathrm{p} \rightarrow (uud) \qquad (5.16)$$
$$Q = +2/3 + 2/3 + (-1/3) = +1 \qquad B = 1/3 + 1/3 + 1/3 = 1$$
$$L_e = 0 + 0 + 0 = 0$$

$$\mathrm{n} \rightarrow (udd) \qquad (5.17)$$
$$Q = +2/3 + (-1/3) + (-1/3) = 0 \qquad B = 1/3 + 1/3 + 1/3 = 1$$
$$L_e = 0 + 0 + 0 = 0.$$

By similar reasoning, the charged pions have a quark content of

$$\pi^+ \rightarrow (u, \text{anti-}d) \qquad (5.18)$$
$$Q = +2/3 + 1/3 = +1 \qquad B = 1/3 + (-1/3) = 0$$
$$L_e = 0 + 0 = 0$$

$$\pi^- \rightarrow (d, \text{anti-}u) \qquad (5.19)$$
$$Q = -1/3 + (-2/3) = -1 \qquad B = 1/3 + (-1/3) = 0$$
$$L_e = 0 + 0 = 0$$

The π^o is actually a sum of (u, anti-u) plus (d, anti-d). The (u, anti-u) component has:

$$Q = +2/3 + (-2/3) = +0 \qquad B = 1/3 + (-1/3) = 0$$
$$L_e = 0 + 0 = 0.$$

The (d, anti-d) component has:

$$Q = -1/3 + 1/3 = +0 \qquad B = 1/3 + (-1/3) = 0$$
$$L_e = 0 + 0 = 0.$$

Both the (u, anti-u) and (d, anti-d) combinations have the same total quantum numbers, and so π^o has $Q = 0$, $B = 0$ and $L_e = 0$.

Addition of the spin quantum number J has not been shown in the examples above, where the other quark quantum numbers have been added together. Addition of spin quantum numbers is a subject taken up in more advanced courses and is more difficult than the addition of scalar quantum numbers like charge 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.

The proton has quark content (uud) and the neutron has (udd). What about all the other baryons? For example, in Table C.6 there are some particles labelled N(1440) *etc.* that have the same quantum numbers as nucleons (i.e., there is an $N(1440)^+$ and an $N(1440)^o$ like p and n). Their quark content is also (uud) and (udd) just like the proton and neutron. However, in the N(1440) the quarks are moving with different angular momentum than the quarks do in p and n, and this makes the N(1440) a different particle with different mass than the nucleon. In fact, there are many situations in which elementary particles have the same quark content but different mass because the relative motion of the quarks is different.

Now, an interesting situation occurs for the combinations (*uuu*) and (*ddd*). 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! (See Sec. 2.C for more details.)

The existence of the Δ^{++} and Δ^{-} indicate that there must be another quantum number associated with quarks: *colour*. This quantum number is not colour as our eye sees it, but is simply a label that is attached to the quarks. The name of the label "colour" is arbitrary. In any event, 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. Hence, the problem of having three fermions with the same quantum number is avoided. The physical consequences of the existence of the colour quantum number have been verified experimentally, and give us confidence that colour is a real quantum number.

In any given hadron, the quarks exchange their colour among themselves so that equal amounts of each colour are present. The colour is carried between the quarks by *gluons*. Gluons are massless, neutral and have J = 1. That is, they are bosons, not fermions like the quarks. The gluons are the gauge bosons of the interaction between quarks, much like the photon is the gauge particle of electromagnetism. Since no free quarks or gluons have ever been observed, one could say that free colour is never observed. The theory of quarks and gluons is referred to as *quantumchromodynamics* or QCD (where the origin of the "*chromo*" should be obvious).

5.D Bosons as Carriers of Force

In the macroscopic world, we are used to the idea of "action at a distance". In the well-known Newtonian example of the motion of an apple falling to Earth, we think of the apple and Earth gravitationally interacting with each other over a distance, without any mechanical contact between them. Similarly, we do not think of the electrostatic attraction between a comb and small bits of paper as needing a material or mechanical contact, at least on the macroscopic scale of things.

However, on microscopic length scales the action-at-a-distance picture fails. It appears that the forces *between* particles are mediated by the *exchange* of other particles. There is no direct evidence for this model of interactions in the sense that we cannot trap a particle as it is being exchanged by a pair of particles. Rather, the evidence is indirect: one constructs models for particle interactions, uses the models to make predictions and compares the predictions with experiment. Thus far, the models that work best for the strong, electromagnetic and weak interactions all involve particle exchange.

Consider the motion of two identical hard spheres (labelled A and B) hitting each other head on. Fig. 5.1 shows the positions of the spheres at three different times: long before the collision (a), at the collision point (b) and long after the collision (c).

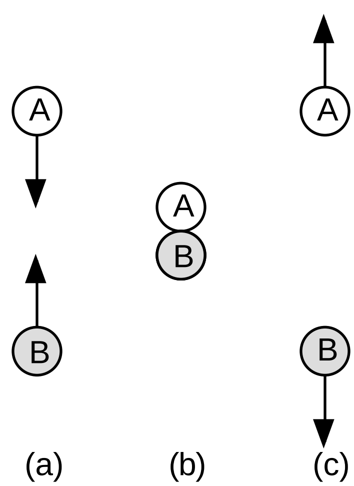


Fig. 5.1. Positions of two hard spheres undergoing a head-on collision, shown at different times: long before the collision (a), at the collision point (b), long after the collision (c). The arrows indicate the direction of motion.

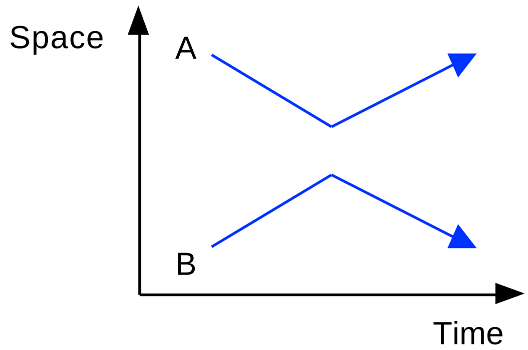


Fig. 5.2. A space-time diagram for the collision in Fig. 5.1. The positions of the particles are shown as a function of the elapsed time.

A space-time diagram provides a better representation of the time evolution of the collision. A space-time diagram for the collision in Fig. 5.1 is shown in Fig. 5.2, which is nothing more than a graph of the particle positions as a function of time. The vertical axis is the spatial position of the particle centres, while horizontal axis is the elapsed time. In Fig. 5.1, 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 Fig. 5.2 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, the elementary particles of light. We visualize this in the space-time diagram shown in Fig. 5.3 (b) for the scattering of two electrons, where the photon is denoted by the Greek letter gamma (γ). While the diagram shows 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 gluons (strong), photons (electromagnetic) and W and Z bosons (weak). The gluons and photons are massless, while the W and Z particles are far more massive than protons.

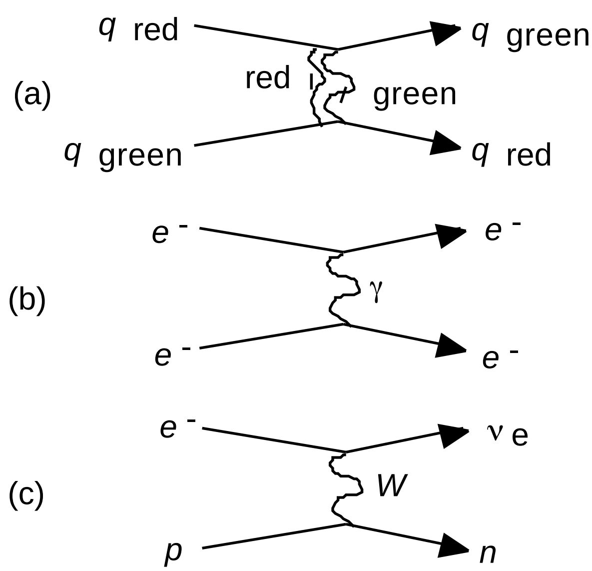


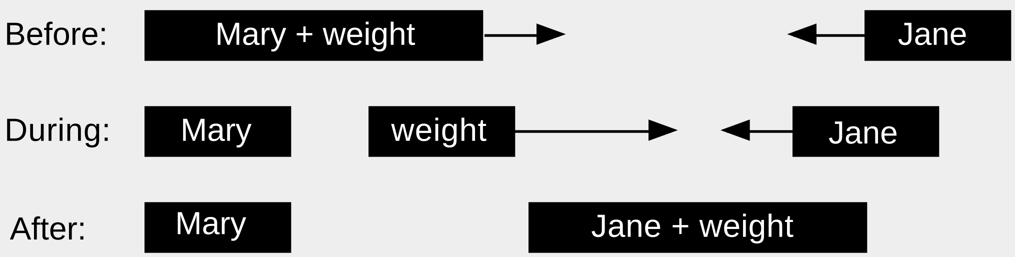
Fig. 5.3. Particle-exchange models for the strong (a), electromagnetic (b) and weak (c) interactions. The exchanged particles are the gluon, photon (γ) and W-boson (W).

Gluon exchange deserves some extra comments. What is shown in Fig. 5.3a are two quarks of unspecified flavour scattering from each other. The top quark in the figure has colour red (*R*) while the bottom quark has colour green (*G*). Under gluon exchange, the quark flavours (i.e., *u*, *d*, *s*...) don't exchange but the colours do. The gluons don't carry quantum numbers like strangeness, charm *etc.* between the quarks but they do carry colour. In the diagram, the gluon carries *R* in a downward direction and *G* in an upward direction. There are also gluons that carry the same colour in both directions.

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 not all nine of these colour combinations are separately allowed. In fact, (anti-*R*, *R*), (anti-*G*, *G*) and (anti-*B*, *B*) can be combined to give only two gluons, so that the total number of gluons is actually 8.

Example 5.3: *The following is a macroscopic example of interaction via particle exchange. Two skaters, Mary and Jane, are moving straight towards each other, each with a speed of 0.5 m/s with respect to the ice. Mary has a mass of 49 kg and is carrying a 1 kg lead weight, while Jane has a mass of 50 kg. They wish to avoid collision by exchanging the lead weight, which one skater will throw to the other. With what velocity relative to the ice must the weight be thrown to bring the skaters to a stop in one throw?*

This is a problem in the conservation of momentum. Let us assume that Mary is moving in the positive *x*-direction, while Jane is moving in the negative *x*-direction.



Mary throws the weight at such a speed that she comes to a complete stop after she releases the weight. The initial momentum of herself plus the weight is equal to the mass of Mary plus the weight (50 kg) times the velocity of Mary plus the weight (0.5 m/s), or 25 kg-m/s. If the weight carries off all of the momentum which Mary and the weight initially have, then it must have a momentum of 25 kg-m/s after release. Thus, the speed of the weight with respect to the ice must be 25 (kg-m/s) / 1 kg = +25 m/s.

What happens to Jane after she catches the weight? Jane's initial momentum is -25 kg-m/s. When she catches the weight, the total momentum of herself plus the weight will be -25 + 25 = 0 kg-m/s. So Jane will come to a stop after catching the weight, just as Mary came to a stop after throwing the weight. Whether Jane is still standing after catching the weight is a separate issue. The weight is travelling at a speed of 25 m/s, or 90 km/hr! To avoid falling down, the skaters would be better off to exchange the weight many times at a low velocity, rather than once at a high velocity.

The particle-exchange model for the electromagnetic interaction has been very thoroughly tested. The exchange model for the weak interaction involves the exchange of *W* and *Z* bosons. Unlike the massless photons that mediate the electromagnetic interaction, the *W* and *Z* particles have masses of 1.44 x 10^{-25} kg and 1.63 x 10^{-25} kg respectively, almost 100 times heavier than the proton mass (see Table 2.2 or Table C.3). The *W* has two charge states (W^+ and W^-) and the Z^o is electrically neutral. While the existence of the *W* and *Z* bosons is known experimentally, the weak interaction theory is less well tested than the electromagnetic theory, mainly because of the high bombarding energies needed to make the tests using scattering experiments. However, 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. Since free quarks and gluons have yet to be seen in Nature, all of the experimental tests must involve hadrons. 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.

What about gravity? 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 (see Chap. 1), gravitons are very difficult to measure, and no convincing evidence for freely propagating gravitons has been found yet.

One note of caution. The results of "classical" studies of electricity and gravity such as Coulomb's law [$F=kQ_1Q_2/r^2$] and Newton's law of universal gravitation [$F=Gm_1m_2/r^2$] do not apply under all conditions, particularly at extremely short distances. These laws were discovered years before the particle exchange models were formulated and tested. At short distances, the particle exchange models have a different form than the classical expressions. 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.

Summary

There may be several different interactions at work in a given reaction or decay process. To find the most important interaction in a process, we apply the following "rules of thumb":

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

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.

If the sum of a particular quantity (e.g., charge) is the same both before and after a reaction or decay, that quantity is said to be *conserved*. Energy, momentum and charge are all known to be conserved to high accuracy. Baryon number and lepton number also are conserved to the limit of current experimental tests.

Within a hadron, the quantum numbers are carried by fermionic constituents called *quarks*. A baryon is composed of three quarks (and an antibaryon of three antiquarks) while a meson is a quark-antiquark pair. There are six flavours of quarks (u, d, s, c, b and t) and each flavour comes in three colours (red, green and blue). Colour is carried between quarks by *gluons*.

At a microscopic level, the interaction between particles is governed by the exchange of *gauge bosons*. The gauge bosons of the electromagnetic (γ) and weak (W^+, W^- and Z^o) interactions can be seen experimentally. The gauge particles of the strong interaction are gluons which carry colour between quarks. Although the effects of gluons can be observed in scattering experiments, no free gluons have been measured.

<u>Further Reading</u>

R. A. Carrigan, Jr. and W. P. Trower, *Particle Physics in the Cosmos* (Freeman, New York, 1989), Secs. III and IV.

F. Close, *The Cosmic Onion* (Heinemann, London, 1983), Chaps. 5 - 8.

B. McCuster, *The Quest for Quarks* (Cambridge, London, 1983), Chaps. 3 - 5.

R. Omnes, *Introduction to Particle Physics* (Wiley, London, 1970), Chap. 2.

M. Riordan, *The Hunting of the Quark* (Simon and Schuster, New York, 1987) [general reading].

J. S. Trefil, *From Atoms to Quarks* (Scribners, New York, 1980), Chaps. 8 - 13.

Problems

1. Find which interaction dominates each of the following reactions:
(a) $p + p \to p + n + \pi$
(b) $\pi + \pi \to \pi + \pi + \gamma$
(c) $\nu + p \to p + \pi + e$
(d) $e^+ + e^- \to \gamma + \gamma$.

2. Find which interaction dominates each of the following processes, and estimate the timescale for the process:
(a) $e + p \to n + \nu$
(b) $\pi \to e + \nu_e$
(c) $\rho \to \pi + \gamma$
(d) $\pi \to \gamma + \gamma$.

3. Order the following decays according to their expected lifetimes (some of the lifetimes may be similar):
(a) $n \to p + e + \nu$
(b) $\omega \to \pi + \pi$
(c) $\omega \to \pi + \gamma$
(d) $\rho \to \pi + \pi$.

4. Order the following reactions according to their expected cross sections:
(a) $\gamma + p \to \pi + p$
(b) $\pi + p \to n + \pi$
(c) $\pi^+ + e^- \to \gamma + \nu_e$
(d) anti-p + p $\to \gamma + \gamma$
(e) $\pi + \pi \to \gamma + \gamma$.

5. List all conservation laws that the following reactions violate (ignore spin):
(a) $\pi^o \to e^+ + e^- + \nu_e$
(b) $\pi^+ + n \to e^+ + p$
(c) $p + n \to \pi^o + \pi^+$.

6. Specify the charges of the particles in each of the following reactions:
(a) p + p → p + n + π
(b) ρ → π + γ
(c) π → γ + γ.

7. Specify the complete charge and antiparticle labels for each of the particles in the following reactions:
(a) anti-n → anti-p + e + ν_e
(b) π^- → e + ν_e
(c) ρ^o → π + π
(d) e + e → γ + γ.

8. Find all possible quark-antiquark states made from the *u*, *d* and *c* quarks. What are the charge, baryon number and lepton number of each state? If $m_u = m_d << m_c$ which states have equal mass?

9. Find all possible 3 quark states which can be made from *u*, *d* and *s* quarks. What are the charges and baryon numbers of each particle? Assume that the masses of the quarks have the order $m_u = m_d << m_s$ and calculate the order of the masses of the particles.

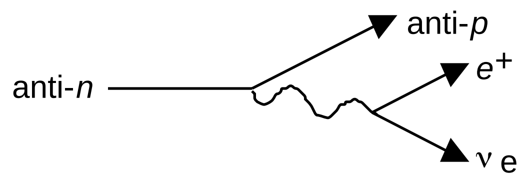
10. Find all possible 3 quark states which can be made from *c*, *b* and *t* quarks. What are the charges and baryon numbers of each particle? Calculate the particle masses assuming that the masses of the quarks are $m_c = 1.5$, $m_b = 4.5$ and $m_t = 190$ in terms of proton masses.

*11. One model for the strong attractive force between two quarks is $F = C$, where C is a constant. That is, the force is *independent* of the separation distance between the quarks.
(a) Find a value for C such that the strong force between two *u* quarks overcomes the electrostatic repulsion between the quarks at a separation distance of 0.5 fm.
(b) Use Eq. (A.16) to obtain an expression for the work required to separate two quarks according to the force law in (a). What work is done against the strong force in separating the two *u* quarks in (a) to a separation of 0.5 fm?

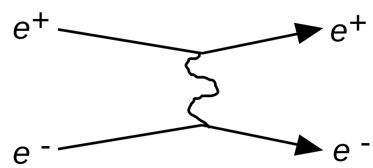
*12. An unknown particle X is observed to scatter from a proton target with a cross section of 10^{-36} m^2. When X decays, its decay products always include a neutrino.
(a) Is X a baryon, meson or lepton?
(b) Is X charged or neutral?

13. In each diagram there is an unknown gauge particle indicated by the wavy line. The identity of the gauge particle can be found by knowing which interaction is involved, and by applying the conservation laws (Q, B and L_e) at each vertex. Find the complete labels for the unknown particles:

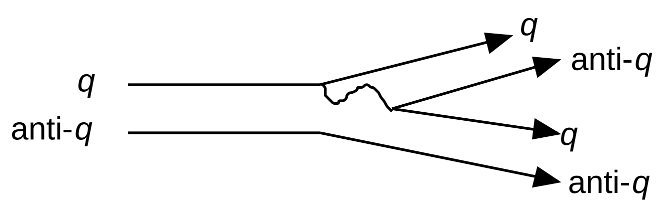
(a) anti-n → anti-p + e^+ + ν_e (weak)



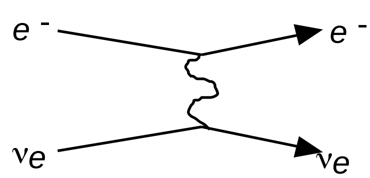
(b) $e^+ + e^- \rightarrow e^+ + e^-$ (e-m)



(c) $\rho \rightarrow \pi + \pi$ (strong)



(d) $e^- + \nu_e \rightarrow e^- + \nu_e$ (weak)



14. The discovery of the "top" or t quark was recently announced, and it is estimated that the top quark is 170 times as massive as the proton. Find all possible meson states that can be made from s, b and t quarks, and give the charge, baryon number and lepton number of each meson. Assuming that the masses of the quarks in this question are

$$m_s = m_b / 10 \quad \text{and} \quad m_b = m_t / 35,$$

list the meson states, and their quantum numbers, in order of increasing mass.