CHAPTER 2

INTERACTIONS I

2.A Four Fundamental Interactions

Our discussion of the fundamental forces in Nature begins with gravity, the most familiar force in everyday life. The inverse square law form for the gravitational force was hypothesized as early as 1640. It was in 1665 or 1666 that Sir Isaac Newton (1642-1727) first extracted the inverse square law for gravity from observation by comparing the acceleration due to gravity on the surface of the Earth with the acceleration due to gravity experienced by the Moon in its orbit around the Earth. Newton did not actually publish all of his work on gravitation until twenty years later in *Philosophiae Naturalis Principia Mathematica*, after it was proven in 1684 that a spherical object acted as if its mass were concentrated at its centre. We know that the inverse square law accurately describes most gravitational phenomena in everyday experience, although Einstein's theory of relativity shows us that there are examples of gravitational phenomena that cannot be explained using Newton's theory.

Mathematically, Newton's Law of Universal Gravitation states that the force of attraction between two objects with masses m_1 and m_2 is given by

$$F = Gm_1m_2/r^2 \tag{2.1}$$

where r is the distance between the objects. The law is universal in the sense that the gravitational force between objects does not depend on the material from which the objects are made. There are some obvious questions about how to use Eq. (2.1) when objects have strange shapes or are close together, but all of these issues are straightforward to handle. The constant G appearing in Eq. (2.1) is a universal constant and is equal to

6.67×10^{-11} Nm^2/kg^2. Gravity is such a strong force in our macroscopic world because of the immense masses involved when, for example, we consider the attraction between our bodies and the Earth. We see from Example 2.1 that at a microscopic level, the gravitational attraction between particles is tiny.

Example 2.1: *Use Newton's Law of Gravitation to calculate the gravitational attraction between two protons separated by a distance of 1 fm (i.e. 10^{-15} m).*

This problem involves a simple substitution:

$F = Gm_p m_p / r^2$

$= [6.67 \times 10^{-11}]\,[1.67 \times 10^{-27}]^2 \,/\, [1 \times 10^{-15}]^2$

$= 1.86 \times 10^{-34}$ N.

Clearly, the gravitational force between protons is not very large.

A second force with which we are familiar from the macroscopic world is the interaction between charged objects. A mathematical form for this force was developed by Charles Augustin de Coulomb (1736-1806) a century after Newton. Coulomb's Law states that the magnitude of the force between two objects with charges Q_1 and Q_2 separated by a distance r is given by

$$F = k|Q_1 Q_2| / r^2. \qquad (2.2)$$

In Eq. (2.2), the constant k is equal to 8.99×10^9 Nm^2/C^2.

Although force is a vector quantity, Eqs. (2.1) and (2.2) give only the magnitude of the force. The gravitational force is always attractive: the force a body experiences due to its gravitational interaction with another body points towards the other body. The electrostatic interaction is different: charges with the same sign repel, while charges with opposite signs attract. Hence, the signs of the charges must be taken into account when we evaluate $\boldsymbol{F}$ (vector) rather than F (scalar).

Example 2.2: *Calculate the Coulombic repulsive force between two protons separated by a distance of 1 fm (i.e. 10^{-15} m). The electric charge of a proton is exactly opposite to that of an electron.*

As with Example 2.1, this problem involves a straightforward substitution. The magnitude of the force is

$$F = k|Q_p Q_p|/r^2$$

$$= [8.99 \times 10^9]\,[1.6 \times 10^{-19}]^2 \,/\, [1 \times 10^{-15}]^2$$

$$= 230 \text{ N}.$$

The magnitude of the electrostatic force is immense compared to the gravitational force calculated in Example 2.1. To use a macroscopic comparison, the electrostatic repulsion between two protons in a nucleus is between a third and a half the gravitational force that the entire Earth exerts on the average student. A student of mass 50 kg experiences a force of 490 N on the surface of the Earth.

Our everyday world tells us that there are at least two fundamental forces: gravity and electromagnetism. The term *electromagnetism* is used to denote both electric and magnetic forces, which are known to have a common origin. We also know from our examples that the strengths of these forces differ by many orders of magnitude. However, there is ample evidence that these are not the only two forces in Nature. The attraction between negatively charged electrons and the positively charged nucleus results in a bound state: the atom. But then, why is the nucleus bound if it carries a net positive charge? Examples 2.1 and 2.2 demonstrate that the gravitational attraction between the protons in a nucleus is far too weak to overcome the electrostatic repulsion. So there must be another force which acts among nucleons and holds the nucleus together. We call this the *strong interaction*. Evaluating the magnitude of the strong interaction is a difficult task, and there is no simple functional form like Eq. (2.1) or (2.2) for the separation dependence of the strong force. However, the strong interaction must have a greater strength than the electrostatic interaction or it would not be able to bind nucleons together.

To date, we know of only one further force in nature beyond the strong, electromagnetic and gravitational interactions: the *weak* *interaction*. Although evidence for this interaction first was observed in the decay of free neutrons, more dramatic effects of the weak interaction are seen in the scattering of neutrinos. A neutrino, which is produced in neutron decay and other reactions, interacts only by weak and gravitational interactions. Neutrinos are produced copiously in the nuclear reactions of the Sun, so copiously that more than 10^{10} of them strike every square centimeter of our bodies facing the Sun. Yet we hardly suffer from "neutrino-burns" when we lie on the beach, since the average neutrino literally can pass through a light-year of material, more than a million-million kilometers, before it scatters! The weak interaction is obviously much weaker than the electromagnetic interaction, but it is still stronger than gravity.

Are all particles subject to all interactions? Certainly, all particles are subject to gravity. However, particles must be charged or have an internal charge distribution in order to be subject to the electromagnetic interaction. Similarly, the strong interaction is not felt by all particles. For example, if the electron were subject to the strong interaction, it would orbit the nucleus much more closely than it does in an atom.

2.B Interaction Characteristics

Scattering and decay processes can be used to determine interaction characteristics. Let's return to the way we introduced scattering in Section 1.A: sticky marbles dropped on an apple in a box. The interaction between the marbles and the apple is *short-ranged*, by which we mean that a marble only sticks if its surface touches the apple's surface. Geometrically speaking, the centre-to-centre distance between the marble and the apple must be less than or equal to the sum of the apple and marble radii. Further, *all* marbles satisfying the distance criterion stick to the apple, meaning that it is a very strong interaction over the distance which it acts.

In contrast, consider the situation of waves travelling on the surface of water. When waves come together from different directions they interfere with each other: we see two waves with a height of, say, half a meter, producing waves with a height of one meter as they pass through each other. But the point is that the waves *do* pass through each other; they do not stop each other. In other words, the cross section for water-waves scattering on water-waves is very small even though the physical size of the water waves is of the order meters.

At this point, it may seem counter-intuitive that objects (like water waves) can have cross sections much smaller than their geometrical size. By "geometrical size" we mean the size of an object associated with the separation in space of its constituent parts: an object composed of three marbles glued together in a triangle has a geometrical size determined by the spatial separation of the marbles' centres. However, the cross section σ is only related to the probability of scattering in Eqs. (1.1)-(1.3): if the probability of scattering is zero, then the scattering cross section is zero as well. The correspondence between σ and the geometrical size of an object only strictly applies to particles which scatter with a strong short-ranged interaction. In the marble/apple language of Chap. 1, the sticky marbles have a strong, short-ranged interaction (they always stick if they hit the apple's surface, otherwise they pass by) so the marbles measure the geometrical size of the apple's surface. In a long-ranged interaction, between two magnets for example, σ could be much larger than the geometrical size of the objects. In contrast, with a weak interaction, such as that between water waves, σ could be much less than the geometrical size.

The measured cross section, then, depends on the interaction between the particles. It is entirely possible for an electron scattering from a proton to give a different cross section than a proton scattering from a proton, both in magnitude and in the dependence of the cross section on the angle through which the beam particles are scattered by the target. The angular dependence of the cross section found with *either* probe (electrons or protons as beam particles) can be used to determine the geometrical structure of the proton, i.e. determine the average separation between the quarks in the proton. We expect, and we find, that geometrical information extracted from an analysis of cross section measurements is consistent between different scattering experiments, even though the cross sections themselves are not the same.

Experiments done with protons scattered from nuclei show that the strong interaction is short-ranged and has cross sections in the 10^{-28} - 10^{-30} m^2 range (although there are notable exceptions). Electromagnetic cross sections can be measured by scattering light from protons. The electromagnetic interaction is found to be long-ranged, with typical cross sections of 10^{-36} m^2. This cross section is much smaller than the strong interaction cross section and just reflects the relative weakness of the interaction. It does not mean that an electron beam sees a geometrically "smaller" target proton than a proton beam sees. Weak interaction cross sections can be measured using neutrinos, which are massless particles with no charge and no strong interactions. Typical cross sections for low energy neutrinos are in the range of 10^{-42} m^2 range. The weak interaction is short-ranged.

A brief aside on units. Because the elementary particle cross sections are so small, researchers find it convenient to define a tiny unit of area called a *barn* (as in barn door, and abbreviated as b), such that 1 barn = 10^{-28} m^2 or 100 fm^2. In terms of barns, the strong, electromagnetic and weak interaction cross sections are typically 0.01 - 1.0 b, 10^{-8} b and 10^{-14}b, respectively. In these lectures, cross sections will be quoted in m^2, although the summary of cross sections in Table 2.1 is given in both m^2 and b.

Example 2.3: *A neutrino is a massless, uncharged particle that interacts via the weak interaction. It can pass through a lot of material without being scattered or stopped. Assuming that an atom has a radius of 0.2 nm, estimate how many atoms it takes to scatter a neutrino if its reactions have cross sections of 10^{-42} m^2.*

The area of the atom facing the neutrino is roughly πr^2 = 12 x10^{-20} m^2. But the neutrino sees an effective area of only 10^{-42} m^2, so that its probability of scattering from a given atom is about 10^{-42} / 12 x 10^{-20} = 8 x 10^{-24}. If the probability for the neutrino to scatter from a given atom is 8 x 10^{-24} or about 10^{-23}, then it would take about 10^{+23} atoms lined up one after another in the neutrino's path before the neutrino is likely to be scattered. Again, if each atom has a radius of 0.2 nm, the length of these atoms placed one next to the other in a line would be 10^{23} x 2 x 0.2 x 10^{-9} = 4 x 10^{13} m. This is an immense distance and can be compared with the distance that light travels in one year (called a *light year*): 3 x 10^8 [m/s] x 3.16 x 10^7 [s] = 9.5 x 10^{15} m. We conclude that it takes a *lot* of material to scatter a neutrino.

Decay rates also can be used to measure interaction strength. For example, there is a particle called a pion (π) which has a mass of about 1/7 of the proton mass. Pions come in three different charge states: π^+, π^- and π^o, with the charge Q equal to $+e$, $-e$ and 0 respectively, where e is the elementary unit of charge equal to 1.6 x 10^{-19} Coulombs. The two charged pions decay via the weak interaction with a lifetime of 2.6 x 10^{-8} seconds (the exact meaning of the word "lifetime" is given in Chap. 6). The main decay mode of a charged pion is via the weak interaction

$$\pi \rightarrow \mu + \nu \tag{2.3}$$

where the muon, μ, is a particle with 1/9 of a proton mass and the neutrino, ν, is a massless particle that travels at the speed of light. The neutral pion decays into two gamma rays (γ) via the electromagnetic interaction

$$\pi^o \rightarrow \gamma + \gamma \tag{2.4}$$

with a lifetime of 8 x 10^{-17} seconds. The fact that the π^o decays so much faster than the charged π^+ or π^-, by about $10^{-8}/10^{-16} = 10^{+8}$, is a result of the interaction strength: the stronger the interaction, the faster the decay (all other things being equal). The π^o decays via the electromagnetic interaction, whereas the π^+ and π^- decay via the weak interaction. Weak interaction decays occur slowly and hence particles which decay via the weak interaction have long lifetimes. A further illustration of this effect is the decay of the rho meson (ρ). The ρ has a mass equal to about 5 pion masses, and it decays predominantly by

$$\rho \rightarrow \pi + \pi. \tag{2.5}$$

This is a strong interaction decay, and the lifetime of the ρ is an exceedingly short 4.4 x 10^{-24} seconds.

We see from the above that stronger interactions show larger cross sections and shorter lifetimes because there is greater interaction among the participants of the reaction or decay. Typical cross sections and lifetimes are summarized in Table 2.1. Many possible processes involving the different interactions can play a role in a given particle decay or reaction. That is, when particle A decays to particles B and C in $A \rightarrow B + C$, there may be several different interactions present at the same time among the particles. The interaction that determines the overall lifetime

Table 2.1 Characteristics of the four fundamental interactions. Also shown are typical elementary particle cross sections and decay lifetimes corresponding to these interactions. The cross sections and lifetimes are for comparative purposes only; each value spans many orders of magnitude, depending on the participants in the process.

Interaction	Range	Strength	Cross section (m^2)	(b)	Lifetime (s)
Strong	short	strong	10^{-30}	10^{-2}	10^{-24}
Electromagnetic	long	medium	10^{-36}	10^{-8}	10^{-16}
Weak	short	weak	10^{-42}	10^{-14}	10^{-8}
Gravity	long	very weak			

or cross section is the strongest one allowed for the process. If all the particles *A*, *B* and *C* can interact via both the strong and electromagnetic interactions, then the strong interaction will dominate, although the electromagnetic interaction is still present. Some operational rules for determining which interactions can play a role in a given process are summarized in Sec. 5.A.

2.C Particle Classifications

Elementary particles can be conveniently classified according to their interactions. The largest family of particles is the *hadrons*, which includes all particles with strong interactions. This family gets its name from the Greek word for strong. Of the particles we have mentioned so far, the proton, neutron, pion and rho are all hadrons. Particles which do not have strong interactions include *leptons* (from a Greek word meaning lightweight) and several of the *gauge bosons*. The electron and neutrino are leptons while the photon is a gauge boson.

As we discuss in Section 5.D, interactions are thought to be carried between elementary particles by carriers sometimes called *gauge bosons*. The electromagnetic interaction is thought to be transmitted by the photon, which is the elementary particle of light, so the photon is a called a gauge boson. Why isn't the photon, which does not have strong interactions, also a lepton, since leptons do not have strong interactions? The answer lies in the spin of the photon, as we explain in a moment. Fortunately, there are not too many kinds of gauge bosons in nature.

What else characterizes an elementary particle other than its interactions? Well, obviously there is its mass: all electrons have exactly the same mass, all protons have exactly the same mass *etc*. There is also its charge: all electrons have a charge of $-e$ and all protons have a charge of $+e$, where e is the elementary unit of charge defined as $e = 1.6 \times 10^{-19}$ C. In fact, all the particles which we observe in nature (except the quarks, but we haven't really observed quarks yet) have a charge that is an integer multiple of e. It should be emphasized that these masses and charges are not just approximately the same, in the way that two apples might have approximately the same mass; the mass and charge of electrons is *exactly* the same for all electrons. When we find that a particular quantity takes on only certain discrete values, rather than a continuum of values, we say that the quantity is *quantized*. Here, we see that electric charge is quantized, and e is called the *quantum* (or basic unit) of electric charge. The number which multiplies the quantum to give the value of the observable is referred to as the *quantum number*.

Do particles possess other quantized observables than their charge? Yes, in fact they have many quantum numbers. One of the most important is the spin angular momentum. The angular momentum of a particle is a measure of its rotational motion, and is described in more detail in Appendix A.III. For a point particle with momentum p travelling in a circular path of radius r, the magnitude of the angular momentum is rp, as measured around an axis through the centre of the circular path and perpendicular to the plane of the path. For a fixed r, the angular momentum increases with p. It is found that spin angular momentum is quantized in units of $h/2\pi$, where h is Planck's constant and has the numerical value of 6.626×10^{-34} Joule-seconds. The spin quantum number is given the symbol J and is a non-negative number from the set 0, 1/2, 1, 3/2, 2, 5/2.... (As a technical aside, the magnitude of the angular momentum vector for a particle with spin quantum number J is $(J[J+1])^{1/2}$ $[h/2\pi]$.)

Particles can be classified into two groups according to their spin quantum numbers:

$J = 1/2, 3/2, 5/2, 7/2......$	fermions	(2.6a)
$J = 0, 1, 2, 3, ...$	bosons.	(2.6b)

Put more generally, $J = n + 1/2$ for fermions and $J = n$ for bosons, where n is zero or a positive integer. The first group (2.6a) are called *fermions* because they possess a symmetry property discovered by two twentieth-century physicists: Enrico Fermi (1901-1954) and Paul Dirac (1902-1984). The *bosons* (2.8b) have a symmetry property discovery by S. N. Bose (1894-1974) and Albert Einstein (1879-1955). The symmetry referred to is a property of the particles when there are two or more of the same type of particles present in a group. In a group, no two fermions can have exactly the same quantum numbers; in contrast, two or more bosons are allowed to have the same quantum numbers.

Examples of particle spins are:

hadrons: p, n; leptons: e^-, ν	$J = 1/2$	
hadrons: π^+, π^o, π^-	$J = 0$	(2.7)
gauge boson: γ	$J = 1$.	

Table 2.2 Gauge bosons of the fundamental interactions. Each gauge boson is listed beside the fundamental interaction with which it is associated. The existence of gluons and gravitons is inferred from experiment, but neither of these gauge bosons has been seen in isolation. A version of this table which also includes the mass energy equivalents is given in Appendix C, Table C.3.

Symbol	Name	Interaction	Mass (kg)	J (spin)
g	gluon	strong	cannot be isolated	1
γ	photon	electromagnetic	$< 5 \times 10^{-63}$	1
W^+, W^-	W-boson	weak	$(1.44 \pm 0.007) \times 10^{-25}$	1
Z^o	Z-boson	weak	1.63×10^{-25}	1
	graviton	gravity	predicted to exist	2

Now that we have described spin, we return to the question of how do gauge bosons differ from leptons? Table 2.2 shows the currently expected family of gauge bosons. In Table 2.2, we see that all of the observed gauge particles have $J = 1$, and are therefore bosons, as their name states. Further, there is also a spin characteristic of the lepton family: *leptons* are *fermions.* Thus, the photon is not a lepton because it has $J = 1$, among other things. It is interesting to note that the electron, which appears to be point-like, and the neutrino, which appears to be massless, both have a non-zero spin quantum number.

The electron is not the only lepton: additional leptons with non-zero mass are the muon and tao, μ and τ respectively. For each lepton with non-zero mass, there is a particular neutrino ν. All neutrinos are leptons and none have a detectable mass. The three types of neutrino, ν_e, ν_μ and ν_τ are all distinct from one another. The leptons are said to form three groups, each with their own quantum number called a *lepton number.* In these lectures, we are only concerned with the lepton number L_e, which is the lepton number associated with electrons:

$$\text{Leptons: } e^-, \nu_e \qquad L_e = 1 \qquad (2.8a)$$

$$\text{Hadrons, gauge bosons: } p, n, \pi, \gamma \ldots \qquad L_e = 0. \qquad (2.8b)$$

A summary of some lepton properties is given in Table 2.3; a more complete description is given of L_μ and L_τ in Appendix C, Table C.4.

Table 2.3 Lepton family of elementary particles. Table C.4 in Appendix C is an extended version of this data, including mass energy equivalents.

Symbol	Mass (kg)	J (spin)	L_e
ν_e	$< 1 \times 10^{-35}$	1/2	1
ν_μ	$< 4.8 \times 10^{-31}$	1/2	0
ν_τ	$< 6.2 \times 10^{-29}$	1/2	0
e^-	9.11×10^{-31}	1/2	1
μ^-	1.884×10^{-28}	1/2	0
τ^-	3.18×10^{-27}	1/2	0

Yet another quantum number, which is somewhat different in its nature than charge or spin, is *baryon number*, B. All hadrons (strongly interacting particles) which are also fermions are called *baryons* (derived from a Greek word meaning heavy) and have $|B| = 1$. All other particles have $B = 0$. For example

Hadrons: p, n	$B = 1$	(2.9a)
Hadrons: π; leptons: e^-, ν; gauge bosons: γ	$B = 0.$	(2.9b)

So baryons are hadronic fermions. Hadronic bosons are called *mesons* (from the Greek word for middle). Both the pion (π) and the rho (ρ) mentioned in Sec. 2.B are mesons.

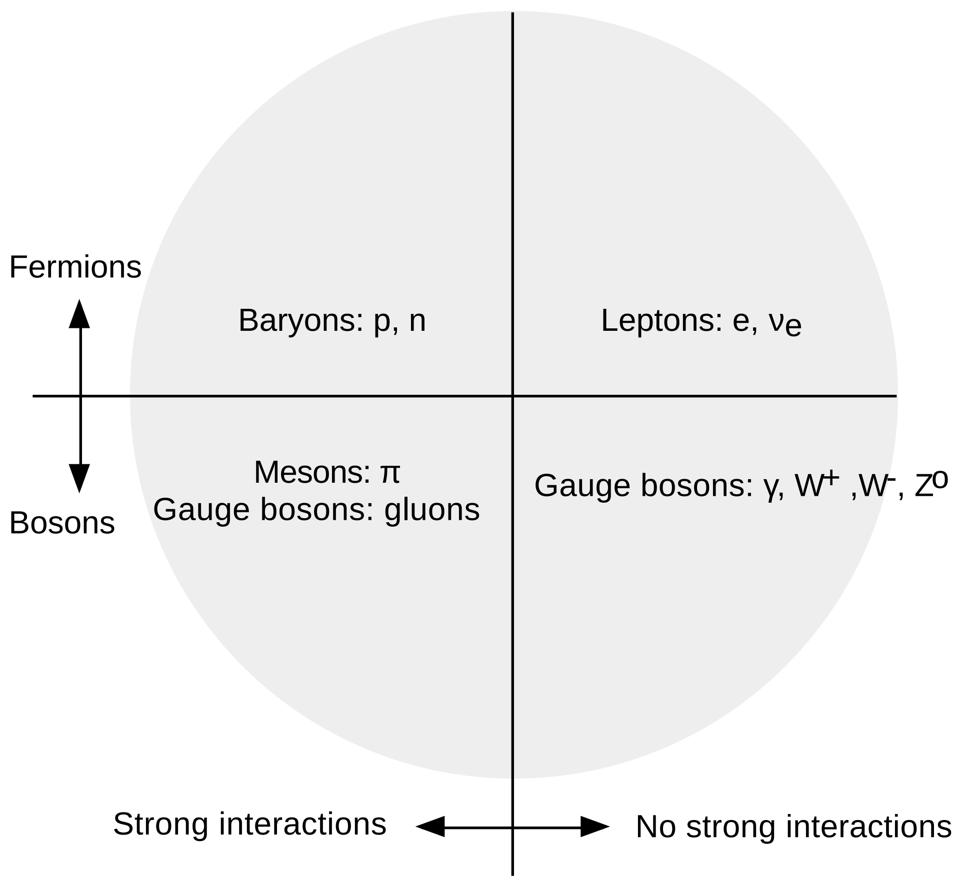

Fig. 2.1 Pie chart of the particle families. The particles shown are referred to throughout these lectures and should be memorized.

Table 2.4 Hadron family of elementary particles. Mesons are hadronic bosons, and baryons are hadronic fermions. More data on hadrons can be found in Appendix C, Table C.5 for mesons and Table C.6 for hadrons. This is a *very* small sampling of the known hadrons.

Symbol	Mass (kg)	*J* (spin)	Charge states	*B*
Mesons				
π^o	2.41×10^{-28}	0	o	0
π^+, π^-	2.49×10^{-28}	0	+, -	0
η	9.79×10^{-28}	0	o	0
ρ	1.37×10^{-27}	1	+, o, - 0	
ω	1.39×10^{-27}	1	o	0
η'	1.71×10^{-27}	0	o	0
φ	1.82×10^{-27}	1	o	0
η_c	5.31×10^{-27}	0	o	0
Υ	1.67×10^{-26}	1	o	0
Baryons				
p, n	1.67×10^{-27}	1/2	+, o	1
Δ(1232)	2.20×10^{-27}	3/2	++, +, o, -	1
Λ	1.99×10^{-27}	1/2	o	1
Σ	2.12×10^{-27}	1/2	+, o, - 1	
Ξ	2.35×10^{-27}	1/2	o, -	1
Ω	2.90×10^{-27}	?	-	1

There are still more quantum numbers than what are described above. The hadrons have many characteristics such as strangeness, charm, beauty *etc.* We defer the introduction of these quantum numbers until the quark substructure of hadrons is presented in Sec. 5.C. A small sample of the hadron family is given in Table 2.4. It is not necessary to memorize the tables to understand the material in these lectures: only the particles listed in Fig. 2.1 are referred to routinely in the following chapters.

2.D Antiparticles

Experimentally, there are many cases in which there are two particles with the same mass, but quantum numbers with opposite sign (in those situations where the quantum number can change sign). For example, both the electron and positron have the same mass but

$$\begin{array}{llll} \text{electron} = e^- & Q = -e & J = 1/2 & L_e = 1 \\ \text{positron} = e^+ & Q = +e & J = 1/2 & L_e = -1. \end{array} \tag{2.10}$$

Note that the spin J is always positive since it is a measure of the magnitude of the angular momentum, not its direction. Pairs of particles such as the electron and positron are said to be *antiparticles* of each other. The electron neutrino ν_e and antineutrino anti-ν_e are also a particle-antiparticle pair. It is arbitrary which one is the particle and which is the antiparticle. The antiparticle is often denoted by the particle symbol with a bar placed over it, but the author has found considerable difficulty in printing overstrikes with a number of commercial word processors, so the notation we use here is simply to put "anti" in front of the particle symbol: for example p (proton) and anti-p (antiproton).

The general rule is that for every particle there is an antiparticle with the same mass but opposite quantum numbers. However, there are cases in which the quantum numbers cannot change sign (like J) or are zero. For example, the neutral pion:

$$\pi^o \qquad Q = 0 \qquad J = 0 \qquad L_e = 0 \qquad B = 0. \tag{2.11}$$

In this case, the quantum numbers of the "anti-pion" π^o would all be zero, just as they are for the pion. In other words, the pion and the "anti-pion" are indistinguishable: there is *no* difference between the particle and the antiparticle. In cases where the particle and antiparticle are indistinguishable, the particle is said to be its own antiparticle. But let's not be misled by the choice of words in this last sentence, the words just mean that the particle does not have a distinct antiparticle.

Summary

There are four fundamental forces known in nature which are, in order of decreasing strength, the strong, electromagnetic, weak and gravitational interactions. The electric (Coulomb) and gravitational interactions have a particularly simple form for point particles, as seen in Eqs. (2.1) and (2.2):

$$F_{coul} = kQ_1Q_2/r^2 \qquad \text{and} \qquad F_{grav} = Gm_1m_2/r^2$$

where Q and m are a particle's charge and mass, r is the point-to-point distance and k and G are 8.99 x 10^9 Nm^2/C^2 and 6.67 x 10^{-11} $m^3kg^{-1}s^{-2}$, respectively.

Particles can be classified by their spin J as either *fermions* (J = 1/2, 3/2, 5/2, 7/2....) or *bosons* (J = 0, 1, 2, 3...). Each interaction is thought to have one or more gauge bosons associated with it: gluons (strong), photons (electromagnetic), W and Z-bosons (weak) and gravitons (gravity). The general classification of particles is shown in Fig. 2.1 or Table 2.5.

Among other quantum numbers which particles can carry are:
Q = charge; quantized in units of e = 1.6 x 10^{-19} C
B = baryon number; baryons have $|B|$ = 1, non-baryons have $|B|$ = 0
L_e = lepton number; hadrons and gauge bosons have L_e = 0.

Table 2.5 Species of elementary particles.

Species	Subspecies	Strong interactions?	Spin type
hadrons	baryons	yes	fermions
	mesons	yes	bosons
leptons		no	fermions
gauge bosons	gluons	yes	bosons
	photon	no	boson
	W, Z	no	bosons
	graviton	no	boson

Particles may have distinct antiparticles which have the same mass but whose quantum numbers have the opposite sign (except for the spin quantum number *J* which cannot be negative).

Further Reading

F. Close, *The Cosmic Onion* (Heinemann, London, 1983), Chaps. 1 - 4.

H. R. Pagels, *The Cosmic Code* (Simon and Schuster, New York, 1982), Part II.

S. Weinberg, *The Discovery of Subatomic Particles* (Scientific American, New York, 1983) [general reading].

Problems

1. Compare the electrostatic attractive force and the gravitational attractive force between an electron and a proton in a hydrogen atom. Take the electron-proton distance to be 0.51 Å.

2. A 30 solar mass star explodes leaving a 1.2 solar mass neutron star among the debris (1 solar mass = 1.99 x 10^{30} kg, the mass of the Sun). A neutron star is made entirely of neutrons and has the same density as a large nucleus.
a) Find the density of a nucleus using Eq. (1.5).
b) Use this density to determine the radius of the neutron star.

3. A neutrino from the Sun strikes the ocean perpendicular to its surface. Estimate the probability that the neutrino will interact as it passes through 3 km of sea water ($n_T = 10^{32}$ m^{-2}).

*4. The number of neutrinos striking the Earth from the Sun is 6 x 10^{10} s^{-1} for a square centimeter area directly facing the Sun. How many neutrinos interact per hour in the body of a person sunbathing on Kits Beach? Assume that the person is facing the Sun with an area of 0.60 m^2 and a number density of n_T = 5 x 10^{27} m^{-2}. Take the cross section for neutrino interactions to be 10^{-42} m^2.

5. A beam of 10^{10} particles per second is incident upon a target with n_T = 5.9 x 10^{23} m^{-2}. Only 10^4 particles are observed to scatter per second. With what interaction is the scattering consistent?

6. Find the probability that a particle will interact (that is, scatter) via (a) strong, (b) electromagnetic and (c) weak interactions in traversing a material with $n_T = 10^{27}$ m^{-2}. State and defend the cross sections that you use in your calculation.

7. Suppose that half of the incoming light which strikes the sea perpendicular to its surface is scattered by the time the light reaches a depth of 1 m of water. Find the cross section for the scattering process by assuming sea water has n_T = 3 x 10^{28} m^{-2}. Compare your result with the geometrical area of a small molecule, say 0.1 nm^2.

8. Classify the following particles as baryons, mesons or leptons:
(a) anti-n (b) π^+ (c) μ^+ (d) ν_μ (e) K.

9. Specify B, L_e and Q of the following particles:
(a) ρ^- (b) N(1440) (c) Σ^+ (d) anti-n.

10. Give the total B, L_e and Q of the following particle pairs by taking the algebraic sum of their quantum numbers:
(a) $\pi^-\pi^o$ (b) $p\pi^-$ (c) $\gamma\gamma$ (d) ne^-.

11. Using the data in Appendix C, find the spins of the following particles and classify them as bosons or fermions:
(a) τ (b) N(1440) (c) ρ (d) π^o (e) Δ(1232).

12. Suppose that a neutron with a speed of 3 x 10^7 m/s is barely captured by an A = 12 nucleus through the strong interaction. Calculate the strong force F acting on the neutron by assuming that the force is constant, and that the neutron travels a distance equal to the nuclear radius R before it stops (see Eqs. (A.16) and (A.17)]. Compare this force to the electrostatic force between two protons in Example 2.2.

*13. Suppose that the charge on the electron was not quite equal to the charge on the proton. Then every "neutral" atom with the same number of electrons and protons actually would have a net charge. In this problem, we try to get a crude upper bound for the net charge.
(a) Assume that the net charge Q of an object is proportional to its mass: $Q = Cm$. Find C assuming that the electrostatic repulsion between the net charge on two objects is equal to their gravitational attraction.
(b) The quantity C in (a) is net charge per kilogram. Convert it to net charge per nucleon, using 1.67 x 10^{-27} kg for the nucleon mass.
(c) What is the ratio of this net charge per nucleon to the proton's charge?