

## 7.2 The Fundamental Forces

In everyday experience, physical objects interact with each other by several different types of forces. For instance, when a person pushing on a table we say that the person is applying a push force on the table, when Earth pulls on a skydiver we say that there is a force of gravity on the skydiver, when two friends are pulling on each other by pulling on a rope we say that there is a tension force on the them, and so on. It turns out that all of these myriads of forces are actually manifestations of only four fundamental forces:

1. **Gravitational force.** This is a universal interaction between all objects, large or small, and is the weakest of all. There is no limitation to the distance beyond which the gravitational force stops to act. Gravitational force is a long-range force.
2. **Electric and magnetic forces.** Electric and magnetic forces appear to be two different types of forces, but James Clerk Maxwell showed that these two forces are different manifestations of the same force. The electromagnetic interaction between two objects occurs when they are electrically charged and also between a charged body and electromagnetic radiation or photon. For the same charged particles at the same distance, electromagnetic force is much stronger than the gravitational force. The electromagnetic force is also a long-range interaction.
3. **Weak force.** The weak force is a very short-range force, being effective only within a distance less than  $10^{-3}$  fm, i.e., within a nucleon. The beta decay of nuclei is due to the weak interaction. In the 1960s and 1970s, a unified theory of electromagnetic and weak interactions was developed which has been verified experimentally. The new interaction is called **electroweak interaction**. The theory showed that, although electromagnetic and weak forces appear very different at everyday low energies, they would merge into a single electroweak force above the unification energy, which is on the order of 100 GeV.
4. **Strong force.** Historically, the strong force refers to the force between nucleons, protons and neutrons, in a nucleus that helps explain the binding of nucleons despite very strong repulsive force between protons. In the modern time, the strong force between nucleons is thought to arise from even more fundamental force between quarks. Quarks are constituents of nucleons and other hadrons, which we will study later in this chapter. The fundamental force between quarks is the color force. We will use the same name - strong force - for both the fundamental strong force and the effective strong force.

## Force Carriers

In the field picture of forces, we envision space to be filled with a force field. We understand the force on a particle by the effect of the force field on the particle. For instance, a charge  $q$  will experience a force  $\vec{F}$  if there is an electric field  $\vec{E}$  at the location of the charge.

$$\vec{F} = q\vec{E}.$$

In this view, the force between two charges  $q_1$  and  $q_2$  is described by electric fields  $\vec{E}_1$  and  $\vec{E}_2$  created by the two charges. The force on  $q_1$  will be

$$\vec{F}_{\text{on } 1} = q_1 \vec{E}_{\text{of } 2},$$

and the force on  $q_2$  will be

$$\vec{F}_{\text{on } 2} = q_2 \vec{E}_{\text{of } 1},$$

Treating forces by using force field is quite adequate for classical physics, i.e. non-quantum physics. The relativistic quantum physics, called quantum field theory (QFT), has introduced a different view of how two particles interact with each other. In QFT, one of the interacting particle emits a force mediator particle, which is then absorbed by the other particle, creating an interaction between the emitting particle and the absorbing particle.

For instance, the electric force between two electrons occurs when one electron emits a photon which is subsequently absorbed by the second electron. A diagram, called the Feynman Diagram, helps visualize the interaction process. Two Feynman diagrams for electromagnetic interaction (a) between electron and electron and (b) between electron and proton are illustrated in Fig. 7.3. In the quantum picture of interaction, a force between particles occurs through exchanging force particles.

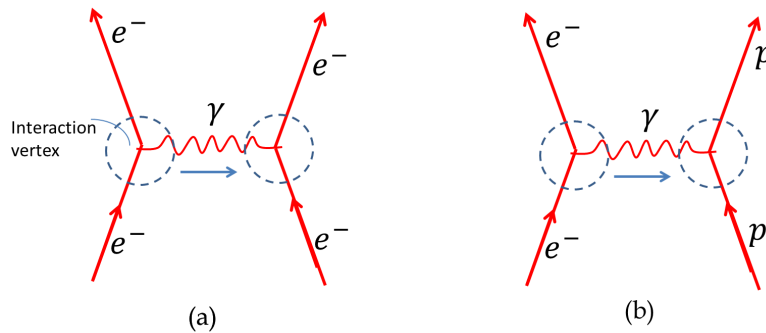


Figure 7.3: Electromagnetic interaction involves exchange of photons between charged particles. These Feynman diagrams show a photon being exchanged (a) between two electrons and (b) an electron and a proton.

Every force is therefore mediated by one or more field particle(s) corresponding to the force. Table 7.1 displays the force carriers for the four fundamental forces and some important characteristics of each force. There is one field particle for

electromagnetic force, three field particles for the weak force, eight for the strong force, and one proposed for gravity. These force-mediating particles are often called **gauge bosons**.

Table 7.1: Fundamental Forces

Force	Range of force	Relative strength	Force carrier
Gravitation	Long	1	Graviton (proposed)
Electromagnetic	Long	$10^{41}$	Photon
Weak	Very short $\approx 10^{-3}$ fm	$10^{37}$	$W^+$ , $W^-$ , $Z^0$
Strong	Short $\approx 1$ fm	$10^{43}$	Gluons (8 types)

### Yukawa Potential

We can illustrate characteristics of force mediators by the treatment of effective strong force between nucleons due to Hideki Yukawa of Japan. Yukawa proposed the following potential  $U(r)$  for the attractive force between nucleons

$$U(r) = -\frac{k}{r}e^{-r/r_0}, \quad (7.5)$$

where  $r_0$  is a parameter with units of length, and  $k$  is a constant signifying the strength of the interaction. If you plot this potential versus  $r$  you will find that the potential decreases to zero more rapidly for smaller  $r_0$  and less rapidly with larger  $r_0$ . That is, the parameter  $r_0$  is a measure of the range of force.

$$r_0 = \text{Range of force.}$$

Yukawa showed that if the range  $r_0$  will be related to the rest mass  $m$  of the force carrier.

$$r_0 \sim \frac{1}{m}.$$

Suppose that  $r_0$  was equal to the de Broglie length of the particle if the particle had a speed close to the speed of light. The, our guess will be

$$r_0 = \frac{h}{p} = \frac{h}{mc}. \quad (7.6)$$

Let us calculate the mass of the force carrier whose range is 10 fm. This will give

$$m = \frac{h}{r_0 c} = \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{10 \times 10^{-15} \text{ m} \times 3 \times 10^8 \text{ m/s}} = 4.42 \times 10^{-28} \text{ kg} = 0.133 \text{ u} = 124 \text{ MeV}/c^2.$$

This should be compared to the mass of pions, with  $\pi^+$  being  $140 \text{ MeV}/c^2$  and  $\pi^0$  being  $135 \text{ MeV}/c^2$ . In the picture of Yukawa, the scattering of a proton and a neutron occurs with an exchange of a pion as illustrated by the Feynman diagram in Fig. 7.4

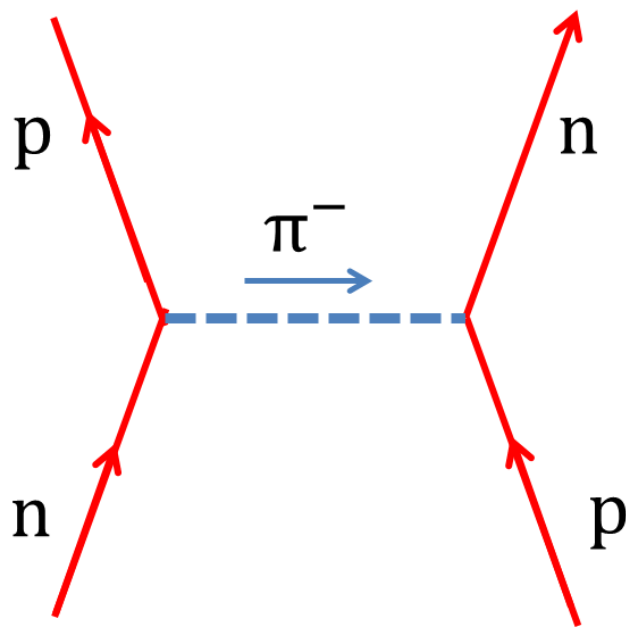


Figure 7.4: Strong force between a proton and a neutron with an exchange of a pion.