20.3: The Electroweak Theory

Type	Charge	Rest energy	Mean life
electron (e^-)	-1	0.000511	stable
electron neutrino (ν_e)	0	≈ 0	stable
muon (μ^-)	-1	0.106	2.2×10^{-6}
mu neutrino (ν_μ)	0	≈ 0	stable
tau (τ)	-1	≈ 1.7	3.0×10^{-13}
tau neutrino (ν_τ)	0	≈ 0	stable

Table 20.3: Table of lepton types, charge (as a fraction of the proton charge), rest energy (in GeV), and mean life (in seconds).

The strong force acts only on quarks and the strong force carrier, the gluon. It does not act on leptons, e. g., electrons, muons, or neutrinos. Table 20.3 shows all of the known leptons. The so-called *weak* force acts on leptons as well as on quarks.

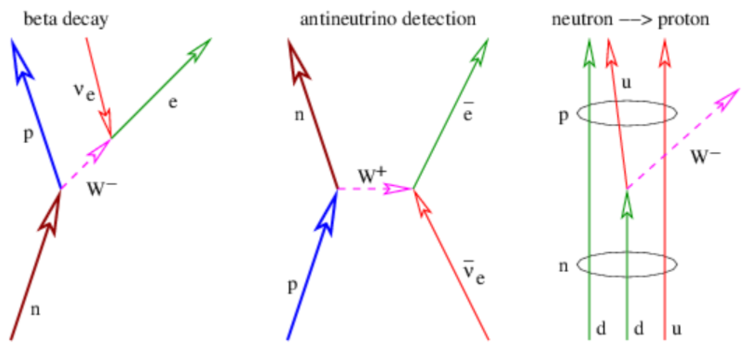

Figure 20.3.3:: Illustration of two weak reactions. The left panel shows beta decay while the middle panel shows how electron antineutrinos can be detected by conversion to a positron. The right panel shows how W^- emission works according to the quark model, resulting in the conversion of a down quark to an up quark and the resulting transformation of a neutron into a proton.

In 1979 Sheldon Glashow, Abdus Salam, and Steven Weinberg won the Nobel Prize for their electroweak theory, which unites the electromagnetic and weak interactions. Unlike the strong and electromagnetic forces, the intermediary particles of the weak interaction, the W^+, the W^-, and the Z^0 have rather large masses. In particular, the rest energy of the $W^\pm$ is 81 GeV while that of the Z^0 is 92 GeV. Electroweak theory considers electromagnetism and the weak interactions to be different aspects of the same force. A key aspect of the theory is the explanation of why three out of four of the intermediary particles of the electroweak force are massive. (The photon is the massless one.) Unfortunately, the details of why this is so are highly technical, so we cannot delve into this subject here. We only note that the explanation requires the existence of a massive spin zero boson called the Higgs particle. As noted previously, this particle has been discovered recently.

The weak force has certain bizarre properties not shared by the other forces of nature:

- The weak interaction can change quark flavors. For instance, the beta decay of a neutron converts a down quark into an up quark. On the other hand, the weak interaction is "colorblind", i. e., it is insensitive to quark colors.
- The weak interaction is not left-right symmetric. In other words, the physical laws governing the weak interaction look different when seen in a mirror.
- The weak interaction is slightly asymmetric to the interchange of particles and antiparticles in certain situations.

The prototypical weak interaction is the decay of the neutron into a proton, an electron, and an antineutrino. This decay is energetically possible because the neutron is slightly more massive than the proton and is illustrated in the left panel of Figure 20.3.3. Note that this figure is drawn as if a neutrino moving backward in time absorbs a W^- particle, with a resulting electron exiting the reaction forward in time. However, we know that this is equivalent to an electron and an antineutrino both exiting the reaction forward in time according to the Feynman interpretation of negative energy states.

The weak interaction is called “weak” because it appears to be so in commonly observed processes. For instance, the range of a relativistic electron in ordinary matter is of order centimeters to meters. This is because the electromagnetic force between the charge of the electron and the charges on atomic nuclei are strong enough to rapidly cause the energy of the electron to be dissipated. However, the range in matter of a neutrino produced by beta decay is many orders of magnitude greater than that of an electron. This is not because the weak force is intrinsically weak — the value of the “fine structure constant” for the weak force is

$$\alpha_w \approx 10^{-2} \tag{20.3.1}$$

according to the standard model, and is actually larger than α for electromagnetism.

The real reason for the apparent weakness of the weak force is the large mass of the intermediary particles. As we have seen, large mass translates into short range for a virtual particle at low momentum transfers. This short range is what causes the weak force to appear weak for momentum transfers much less than the masses of the W and Z particles, i. e., for $q \ll 100$ GeV. For leptons and quarks with energies $E \gg 100$ GeV, the weak force acts with much the same strength as the electromagnetic force.