16.1: The Standard Model of Particle Physics

Our best current understanding of Physics at the most basic level is that it is composed of a number of fundamental particles. These particles are, as best we can tell, points, much like electrons (which are in fact one of the fundamental particles). They have various properties associated with them, including mass, spin (angular momentum), electric charge, and others. It is from these fundamental particles that all of the matter we interact with is built. (However, matter built from these particles only makes up 5% of the total density of the Universe! See Section 16.7.)

Broadly, we can divide the particles into two categories: fermions and bosons. Matter is built from fermions, and the interactions between matter— the four forces— are carried by bosons.

The fermions are divided into three generations; it is only the first generation that we ever interact with on a daily basis. Each generation includes two quarks and two leptons. In the first generation, the quarks are called the "up" and "down" quarks. The two leptons are the familiar electron, and the electron neutrino. Each of the other two generations has an additional two quarks, heavier than the quarks in the first generation; and an additional two leptons, including a heavier version of the electron, and a corresponding neutrino. Additionally, for each fermion, there is a corresponding antiparticle. For example, the anti-electron is called the "positron". Antimatter is rare. In the very early Universe, we believe that matter and antimatter were present in equal quantities, but for some reason that is not understood matter had a slight advantage. A particle of antimatter, when it meets its corresponding matter particle, will mutually annihilate both, releasing their mass as energy according to the conversion $E=mc^2$. That slight advantage that matter had in the very early Universe is what's left over to build up stars, galaxies, and us today.

Table of fermions from the standard model of particle physics. All data is from the PDG (Nakamura and Particle Data Group, 2010). Charges are in units of e, the elementary charge. *: There are three neutrinos. Although masses are not known, we have limits that the heaviest one is less than 18.2 MeV, the middle one is less than 0.19 MeV, and the lightest one is less than 1.3 eV. However, the mass eigenstates and the flavor (i.e. "type of neutrino") eigenstates of the neutrinos are not the same, so it's impossible to identify a given mass with a given type of neutrino.

Generation	Fermion	Symbol	Charge	Spin	mc^2
First	Down Quark	d	-1/3	1/2	5.05 MeV
	Up Quark	u	+2/3	1/2	2.49 MeV
	Electron	e	−1	1/2	0.511 MeV
	Electron Neutrino	ν_e	0	1/2	$*$
Second	Strange Quark	s	-1/3	1/2	101 MeV
	Charm Quark	c	+2/3	1/2	1.27 GeV
	Muon	μ	−1	1/2	106 MeV
	Muon Neutrino	ν_μ	0	1/2	$*$
Third	Bottom Quark	b	-1/3	1/2	4 GeV
	Top Quark	t	+2/3	1/2	172 GeV
	Tauon	τ	−1	1/2	1.78 GeV
	Tau Neutrino	ν_τ	0	1/2	$*$

Quarks are never observed in isolation. For the most part, they are observed in bound states called hadrons. The proton and neutron are two three-quark particles. There is a huge zoo of additional hadronic particles, including baryons (made of three quarks) and mesons (made up of a quark and an antiquark). The proton and the neutron are the only stable hadrons. Indeed, even the neutron is not stable unless it's bound into an atom; a free neutron will decay to a proton, an electron, and an antineutrino in about 15 minutes. "Virtual" mesons are found inside the nucleus. Transient mesons and other sorts of baryons are made in particle accelerators, and also when cosmic rays hit the Earth's atmosphere.

In addition to the fermions that make up matter, there are four forces through which matter interacts. The most familiar of these forces are gravity and the electromagnetic force. In our current theories of physics, gravity is described by General Relativity, and is not included in the Standard Model of Particle Physics. We believe that we will one day be able to produce a working theory of quantum gravity, but we have yet to successfully do that. We expect this theory to include the graviton as a massless spin-2 boson.

The electromagnetic force is the best understood of the four forces. It unifies the electrostatic force and the magnetic force. The photon is the particle that carries the electromagnetic force; we see it as light. Radio waves, infrared radiation, ultraviolet radiation, x-rays, and gamma rays are all forms of light at wavelengths different from those our eye can detect. All of these are made up of photons, the quanta of the electromagnetic field. It is the electromagnetic force that forms the potential in which electrons move in atoms, and it is that interaction that governs the interactions between atoms.

Because the photon and the (presumed) graviton are massless, both gravity and electromagnetism are long-range forces. In contrast, the other two forces are short ranged. The strong nuclear force is the force that binds quarks together into protons and neutrons, and that ultimately binds protons and neutrons together into nuclei. The bosons that carry the strong nuclear force are called gluons. They may be massless, although a moderate mass isn't ruled out. However, other properties of the strong force limit it to a short-range force. The weak nuclear force is, as its name suggests, much weaker than the strong nuclear force, and has only a secondary effect in nuclei. The charge carriers of the weak force are indeed massive, limiting it to a short range force. The weak force is the only force other than gravity that interacts with all of the particles in the standard model. Neutrinos, in particular, only interact via the weak force, making them extremely hard to detect. The weak force is responsible for much radioactive decay; it is a result of the weak force, for instance, that a free neutron will decay into a proton, an electron, and an antineutrino. The bosons that carry the weak force are called "intermediate vector bosons." Their name is the same as their symbol. There are three, the W^+, W^-, and Z^0 bosons.

Table of bosons in the standard model of particle physics. All charges are in units of e, the elementary charge. Not included is the hypothesized graviton, which would be a massless, chargeless, spin-2 boson.

Force	Boson	Symbol	Charge	Spin	Mass
Electromagnetic	Photon	γ	0	1	0
Strong	Gluon	g	0	1	0?
Weak	W^+ W^- Z Boson	W^+ W^- Z^0	+1 −1 0	1 1 1	80 GeV 80 GeV 91 GeV