Chapter 2

Introduction to Particle Physics

If I could remember the names of all the particles, I'd be a botanist.
— Enrico Fermi

Matter

At its most basic level, all matter consists of combinations of 12 elementary particles, which are listed in Fig. 2.1. They can be classified into two groups, leptons and quarks: quarks interact via the strong force but leptons do not. Both types of particles interact gravitationally (i.e., they all have mass) and via the weak force. Finally, all but the neutrinos interact electromagnetically because neutrinos are electrically neutral. The original motivation for the classification of leptons in 1947 was that the electron (the only known lepton at that time) was less massive than the proton and neutron (the only known nucleons—later determined to consist of quarks), and "lepton" is from a Greek word that means small or light. (See page 20.) Of course, after the discovery of the tau lepton in 1975 and the observation that it was almost twice as massive as a proton, the original reason no longer made sense. However, with the discovery of quarks and the fact that they are the only particles to interact via the strong force, the division into leptons and quarks is appropriate, albeit for reasons that have to do with forces rather than mass.[1]

Amazingly, all natural matter that we observe in the world around us consists of only three of these particles: electrons, up quarks, and down quarks. The atoms in our bodies are comprised of electrons as well as protons and neutrons, but the proton is made up of 2 up quarks and 1 down quark (commonly written 'uud'), while the neutron is 2 down quarks and 1 up quark (commonly written 'udd'). In this sense, the universe is very simple. There are only three particles, which combine in a myriad of ways to make up all the wonderful objects that we see: trees, rivers, oceans, mountains, planets, stars, and galaxies.

What are the intrinsic properties of these elementary particles? Two are very familiar, mass and electric charge, and two others, spin and color, are not as familiar. We will

[1] In addition to these 12 particles, there are the so-called "exchange particles," like the photon (denoted by the symbol γ), that mediate the four forces. These particles are also called "gauge bosons," or "intermediate vector bosons," and they are not normally considered to be matter. I will discuss them below on page 22.

e^-	**electron**	Leptons
ν_e	electron neutrino	
μ^-	muon (mu lepton)	
ν_μ	muon neutrino	
τ^-	tauon (tau lepton)	
ν_τ	tau neutrino	
u	**up quark**	Quarks
d	**down quark**	
c	charm quark	
s	strange quark	
t	top (truth) quark	
b	bottom (beauty) quark	

Figure 2.1: The twelve elementary particles that comprise all natural and man-made matter. The three particles in boldface — electron, up quark, and down quark — comprise all known natural matter. There are six leptons (three massive leptons and three massless neutrinos) and six *flavors* of quarks.

examine these four in detail in Sections 2.1 through 2.5. Of course, there are many others, such as strangeness, isotopic spin, lepton number, and baryon number, and we will investigate these in later chapters. The nomenclature of particle physics is very complicated, but if you remember to characterize particles based on their fundamental properties, like mass, charge, etc., it doesn't matter what they are called, you will be able to understand the physics of their interactions with other particles.

You may have noticed that I didn't mention size as an intrinsic property. The reason is that all of these elementary particles are thought to be point-like and have no size. For example, the size of an electron has been experimentally measured to be less than 10^{-22} meters![2] This simply means that the electric force that an electron feels is Coulombic (i.e., $\sim 1/r^2$) down to that distance, which means that there is no reason to think that electrons have any structure at any scale. Of course, when elementary particles combine to form protons, neutrons, atoms, and molecules, the physics of their interaction occurs on a spatial scale so that the conglomerations acquire a characteristic size and shape.

There is another characteristic of these particles that has no classical counterpart: they are identical and indistinguishable. Unlike our macroscopic world, where we can paint seemingly identical objects different colors to distinguish them (billiard balls, for example), in the microscopic world there is no way to tell two electrons apart. When a cue ball, say, collides with an eight-ball and they each move off in different directions, it is clear which ball is which after the collision. However, if two electrons collide and move off, the experimenter is not able to distinguish which electron is which after the collision. As we will see below, this fact has far-reaching implications on the allowable motions of these particles. The most well-known implication is the Pauli exclusion principle that is applied to electrons within atomic orbitals, which I will discuss in Section 4.

[2]Hans Dehmelt, "A Single Atomic Particle Forever Floating at Rest in Free Space: New Value for Electron Radius," *Phys. Scr.* **T22** 102-110 (1988)

e^+	positron (anti electron)	anti Leptons
$\overline{\nu}_e$	anti electron neutrino	
μ^+	anti muon (mu lepton)	
$\overline{\nu}_\mu$	anti muon neutrino	
τ^+	anti tauon (tau lepton)	
$\overline{\nu}_\tau$	anti tau neutrino	
$\overline{\mathrm{u}}$	anti up quark	anti Quarks
$\overline{\mathrm{d}}$	anti down quark	
$\overline{\mathrm{c}}$	anti charm quark	
$\overline{\mathrm{s}}$	anti strange quark	
$\overline{\mathrm{t}}$	anti top (truth) quark	
$\overline{\mathrm{b}}$	anti bottom (beauty) quark	

Figure 2.2: The twelve elementary antiparticles.

Antimatter

Antimatter is as much matter as matter is matter. — Abraham Pais[3]

For every particle, there is a corresponding "antiparticle," with the same mass, but opposite electric charge, and these are listed in Fig. 2.2. The antiparticles are denoted by an overbar, or sometimes by simply changing the sign, as with the positron. Do not ascribe any mysterious properties to antimatter. As Pais implies, from an antiparticle's point of view, *we* are made of "antimatter." In fact, current cosmological theories suggest that in the early universe, a short time after the Big Bang, there was approximately as much matter as antimatter. As the universe cooled, equal amounts of matter and antimatter were annihilated, and what was left over was the small amount of matter that makes up the visible universe. The question of why there was an asymmetry between the amounts of matter and antimatter (i.e., why there wasn't exactly the same amount of both kinds) is one that still has not been answered.

Why, then, does antimatter exist? No one knows, but that appears to be the way the universe is made. However, within the rules of our current structure of theoretical physics, antiparticles are a "necessary consequence of combining special relativity with quantum mechanics."[4] Dirac was the first to realize this fact when he attempted to construct a relativistic wave equation for the electron in 1928 (the Schrodinger equation was not relativistic). The mathematics implied the existence of positive electrons, which later turned out to be positrons.

[3]Abraham Pais is perhaps one of the foremost chroniclers of the story of modern physics. His writings, listed in the Bibliography, are all the more valuable because he was a practitioner — he worked on the front lines in 1940s through the 1970s — and he knew and collaborated with several of the key players personally, e.g., Bohr, Einstein, Heisenberg.

[4]Martin and Shaw, *Particle Physics*, p. 2.