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Chapter 18

FUNDAMENTAL PARTICLES AND FORCES

Since the late 1920's, science has made great strides toward an amazingly comprehensive view of reality with new theories and discoveries about:

- The fundamental particles that make up *all forms of matter*, and the forces that act upon them.
- The origin, evolution and structure of *the universe as a whole*.
- The amazing organization of DNA, the substance within each living cell that encodes genetic information for *all forms of life*.

The discovery of DNA, which is beyond the scope of this book, is the greatest triumph of biophysics, the study of biological phenomena using the principles and techniques of physics.

This chapter describes the "Standard Model", the theory of physics that summarizes the current scientific understanding of elementary particles, the building blocks of matter, and of the fundamental forces by which they interact. The following chapter gives an overview of the universe as a whole.

PARTICLE-ANTIPARTICLE PAIRS

When Dirac combined special relativity and quantum mechanics in 1928, there was a feature of his mathematical solution that appeared meaningless at first. Later, however, it turned into a triumph of theoretical physics.

Dirac's basic equation, which describes the allowed energies for electrons, has two sets of solutions, one positive and one negative. The positive solutions appeared to describe normal electrons. The negative solutions, however, seemed to be physically meaningless. Instead of disregarding them, however, Dirac interpreted them as describing a particle like an electron, having the same mass and the same, but positive, charge. Such a particle, called a "positron", was discovered in 1932 by an American physicist, Carl Anderson, who was not aware of Dirac's theory.

Anderson made his discovery while studying cosmic rays. These are high-energy subatomic particles, which rain down on the earth's atmosphere from outer space. Colliding with atomic nuclei in the atmosphere, cosmic rays generate showers of particles that cascade toward the surface of the earth. In these showers, the enormous energy of the incoming rays is converted into matter, in accordance with Einstein's famous equation $E = m \times c^2$. Among the particles created are pairs of electrons and positrons.

Positrons are not found in ordinary matter, and are very short-lived. When an electron and a positron come together, they annihilate one another, and their combined mass is converted into a high-energy photon. Each of the two particles is said to be the *antiparticle* of the other.

Positrons were the first example of antiparticles to be predicted and later discovered. Except for photons, every subatomic particle detected so far is known to have an antiparticle. In each particle-antiparticle pair, the mass is the same for the two particles, but the electrical charge, or some other property, has opposite values. Photons, which are massless, have no antiparticle counterparts.

SUBATOMIC PARTICLES

In addition to the particles that make up the atom (electrons, protons and neutrons), studies have revealed the existence of hundreds of particles (plus their antiparticles) which are smaller than atoms. These particles do not appear under the low-energy conditions of everyday experience. Also, they quickly decay to the more familiar particles after tiny fractions of seconds.

All these particles can be understood in terms of two types of elementary particles: the "leptons" and the usually more massive "quarks", plus their antiparticles. Both types have no discernible structure; that is, it does not appear that they can be separated into smaller components. Both types appear to behave as points in space, with no measurable size.

Leptons

There are believed to be only six types of leptons (plus their antiparticles). Only two are involved with ordinary matter: the familiar electron, and the chargeless "neutrino." Their antiparticles are the positron and the antineutrino. (Neutrinos and antineutrinos have opposite "spins".)

Neutrinos were thought to be possibly massless. More recent experiments, however, suggest that they do have some mass, but very small.

Neutrinos and anti-neutrinos do not exist within atoms as electrons do. They play an important role in certain types of radioactive decay. In one type, for instance, a neutron changes into a proton, and emits both an electron and an anti-neutrino.

Quarks

There are believed to be only six types of quarks (plus their antiparticles). Only two types of quarks are involved with ordinary matter: the so called "up" and "down" quarks. The up quark has a charge of +2/3e, whereas the down quark has a charge of -1/3e.

Two up quarks and one down quark combine to form a proton with a net charge of +e. Two down quarks and one up quark, instead, combine to form a neutron with zero net charge.

Each of the six quarks comes in three types or "colors" (the term "color" is not to be taken in any literal sense).

Particle Families

The six quarks and six leptons are grouped in three families, each with two quarks and two leptons, as summarized by the table below, which omits all the associated antiparticles.

Table I

	Fermions (24) (each has an antiparticle for a total of 48)			
Family	Quarks (6) (each comes in three "colors" for a total of 18)		Leptons (6)	
#1	up quark	down quark	electron	(electron) neutrino
#2	charm quark	strange quark	muon	muon neutrino
#3	top quark	bottom quark	tau	tau neutrino

The first family consists of the four particles involved with ordinary matter. The second family consists of heavier versions of their counterparts in the first family. Similarly, the third family consists of heavier versions of their counterparts in the second family.

Hadrons

Unlike leptons, quarks are never found as isolated particles. Together with other quarks or antiquarks, they form particles called "hadrons", which divide in two groups called "baryons" and "mesons". Baryons are particles built from three quarks, such as the proton and the neutron. Mesons, on the other hand, are particles built from one quark and one antiquark.

Among the hadrons, only the proton appears to be stable: its lifetime is at least 10^{32} years[8]. A single neutron outside a nucleus, on the average, would

8. In this and the following chapter, we will deal with very very large, as well as very very small, numbers. It becomes then very convenient to use a notation that avoids long strings of zeros.

A notation like 10^{19}, for instance, is used as a shorthand to represent 1 followed by 19 zeros

10,000,000,000,000,000,000

10^{6} then represents one million (1,000,000); 10^{9}, one billion (one thousand millions); 10^{12}, one trillion (one thousand billions, or one million millions).

On the other hand, for very small numbers, as a shorthand, instead of writing, for instance,

0.0000000000000000001

last only 15 minutes before decaying. Inside a nucleus, however, the neutron's lifetime is much longer so that many nuclei can be stable, thus making possible a large variety of chemical elements.

The other hadrons, which number in the hundreds (plus their antiparticles), are all very short-lived, with lifetimes ranging from 10^{-8} to 10^{-23} of a second.

FUNDAMENTAL FORCES

There are believed to be only four fundamental forces in the universe. Two are the already familiar forces of gravity and electromagnetism. The other two are the "strong nuclear force" and the "weak nuclear force", which are active only within the nucleus of the atom.

Of all the forces, the force of gravity is the weakest by far; it is also the most pervasive because its effects can be extremely long-ranging. The electromagnetic force, which affects only charged particles, is about a billion billion billion billion (10^{36}) times stronger than the gravitational force.

The strong nuclear force

The strong nuclear force is the strongest of the fundamental forces. It is typically 100 times stronger than the electromagnetic force, and 100,000 stronger than the weak nuclear force. It is ineffective beyond a range of 10^{-17} of a centimeter. Within the nucleus of the atom, however, it rules supreme.

Baryons (which consist of three quarks) are the particles that feel the strong nuclear force. Mesons (which consist of one quark and one antiquark) play a role in transmitting the strong force, as discussed below. It is the strong nuclear force that binds quarks within neutrons and protons, and holds protons and neutrons within the nucleus, overcoming the powerful repulsive forces among the positively charged protons. The strong nuclear force does not affect leptons.

The weak nuclear force

The weak nuclear force, which affects all particles, has a range shorter than that of the strong nuclear force by a factor of about 1000. It is responsible for certain types of radioactivity. A typical example occurs when a neutron transmutes into a proton.

Bosons

Up until the mid-1800s, before Faraday introduced the concept of field, a force was commonly believed to act at a distance. In the Standard Model, instead, the four fundamental forces are viewed as interactions between particles that

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(1 preceded by 19 zeros, including the one before the decimal point), it is convenient to use the notation 10^{-19}

are mediated by the exchange of other particles called "bosons", which are different for different types of forces.

To get some general idea of how interactions between particles are mediated by an exchange of "messenger particles", think of two people skating toward a common point. One of the skaters carries a football; as he approaches the other skater, he throws him the ball. As a result, the two skaters will change direction, away from one another. One is deflected by the recoil from throwing the ball; the other, by the impact from catching the ball.

There are 12 types of bosons as follows:

- Eight kinds of "gluons", which mediate the strong nuclear force. These are all mesons.
- The familiar photon, which mediates the electromagnetic force.
- Three kinds of "weakons", which mediate the weak nuclear force. They are called W plus, W minus and Z zero, and are (electrically) positive, negative and neutral, respectively.

The 48 matter particles (fermions) previously listed and the 12 force particles above (bosons) constitute all the fundamental particles on which the Standard Model rests.

The gravitational force is believed to be mediated by yet another particle called the "graviton", but its existence has not been experimentally confirmed yet. Like the photon, the graviton would have no mass and no charge, and would travel at the speed of light.

The Standard Model, one of the great accomplishments of contemporary physics, was created by the contributions of many physicists. It is consistent with all experiments performed so far. It has, however, many shortcomings. It does not cover gravity. It does not explain why the various particles have masses that differ so widely. Its complexity leaves physicists striving for a simpler, more unified view of the world.