

Beyond the crystal calorimeter is the hadron calorimeter. As the name suggests, this subdetector measures hadrons such as protons and pions. The hadron calorimeter consists of layers of brass and steel separated by plastic scintillators. Its purpose is to absorb the particle energy and convert it into an electronic signal. Beyond this detector is a large magnetic coil used to produce a uniform field for tracking.

The last subdetector is the muon detector, which consists of slabs of iron that only muons (and neutrinos) can penetrate. Between the iron slabs are multiple types of muon-tracking elements that accurately measure the momentum of the muon. The muon detectors are important because the Higgs boson (discussed soon) can be detected through its decays to four muons—hence the name of the detector.

Once data is collected from each of the particle subdetectors, the entire collision event can be assessed. The energy of the i th particle is written

$$E_i = \sqrt{(p_i c)^2 + (m_i c^2)^2},$$

where p_i is the absolute magnitude of the momentum of the i th particle, and m_i is its rest mass.

The total energy of all particles is therefore

$$E_{\text{total}} = \sum_i E_i.$$

If all particles are detected, the total energy should be equal to the center-of-mass energy of the colliding beam machine (W). In practice, not all particles are identified, either because these particles are too difficult to detect (neutrinos) or because these particles “slip through.” In many cases, whole chains of decays can be “reconstructed,” like putting back together a watch that has been smashed to pieces. Information about these decay chains are critical to the evaluation of models of particle interactions.

11.5 | The Standard Model

Learning Objectives

By the end of this section, you will be able to:

- Describe the Standard Model in terms of the four fundamental forces and exchange particles
- Draw a Feynman diagram for a simple particle interaction
- Use Heisenberg’s uncertainty principle to determine the range of forces described by the Standard Model
- Explain the rationale behind grand unification theories

The chief intellectual activity of any scientist is the development and revision of scientific models. A particle physicist seeks to develop models of particle interactions. This work builds directly on work done on gravity and electromagnetism in the seventeenth, eighteenth, and nineteenth centuries. The ultimate goal of physics is a unified “theory of everything” that describes all particle interactions in terms of a single elegant equation and a picture. The equation itself might be complex, but many scientists suspect the *idea* behind the equation will make us exclaim: “How could we have missed it? It was so obvious!”

In this section, we introduce the Standard Model, which is the best current model of particle interactions. We describe the Standard Model in detail in terms of electromagnetic, weak nuclear, and strong forces. At the end of this section, we review unification theories in particle physics.

Introduction to the Standard Model

The **Standard Model** of particle interactions contains two ideas: *electroweak theory* and **quantum chromodynamics (QCD)** (the force acting between color charges). Electroweak theory unifies the theory of **quantum electrodynamics (QED)**, the modern equivalent of classical electromagnetism, and the theory of weak nuclear interactions. The Standard Model combines the theory of relativity and quantum mechanics.

In the Standard Model, particle interactions occur through the exchange of bosons, the “force carriers.” For example, the electrostatic force is communicated between two positively charged particles by sending and receiving massless photons.

This can occur at a theoretical infinite range. The result of these interactions is Coulomb repulsion (or attraction). Similarly, quarks bind together through the exchange of massless gluons. Leptons scatter off other leptons (or decay into lighter particles) through the exchange of massive W and Z bosons. A summary of forces as described by the Standard Model is given in **Table 11.6**. The gravitational force, mediated by the exchange of massless gravitons, is added in this table for completeness but is not part of the Standard Model.

Force	Relative strength	Exchange particle (bosons)	Particles acted upon	Range
Strong	1	Gluon	Quarks	10^{-15} m
Electromagnetic	1/137	photon	Charged particles	∞
Weak	10^{-10}	W^+ , W^- , Z bosons	Quarks, leptons, neutrinos	10^{-18} m
Gravitational	10^{-38}	graviton	All particles	∞

Table 11.6 Four Forces and the Standard Model

The Standard Model can be expressed in terms of equations and diagrams. The equations are complex and are usually covered in a more advanced course in modern physics. However, the essence of the Standard Model can be captured using **Feynman diagrams**. A Feynman diagram, invented by American physicist Richard Feynman (1918–1988), is a space-time diagram that describes how particles move and interact. Different symbols are used for different particles. Particle interactions in one dimension are shown as a time-position graph (not a position-time graph). As an example, consider the scattering of an electron and electron-neutrino (**Figure 11.12**). The electron moves toward positive values of x (to the right) and collides with an electron neutrino moving to the left. The electron exchanges a Z boson (charge zero). The electron scatters to the left and the neutrino scatters to the right. This exchange is not instantaneous. The Z boson travels from one particle to the other over a short period of time. The interaction of the electron and neutrino is said to occur via the weak nuclear force. This force cannot be explained by classical electromagnetism because the charge of the neutrino is zero. The weak nuclear force is discussed again later in this section.

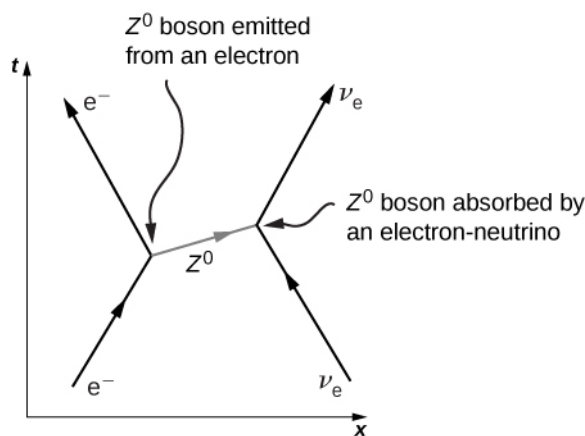


Figure 11.12 In this Feynman diagram, the exchange of a virtual Z^0 carries the weak nuclear force between an electron and a neutrino.

Electromagnetic Force

According to QED, the electromagnetic force is transmitted between charged particles through the exchange of photons. The theory is based on three basic processes: An electron travels from one place to the next, emits or absorbs a photon, and travels from one place to another again. When two electrons interact, one electron emits the photon and the other receives it (**Figure 11.13**). Photons transfer energy and momentum from one electron to the other. The net result in this case is a repulsive force. The photons exchanged are virtual. A **virtual particle** is a particle that exists for too short a time to be observable. Virtual photons may violate the law of conservation of energy. To see this, consider that if the photon transit time Δt is extremely small, then Heisenberg's uncertainty principle states that the uncertainty in the photon's energy, ΔE , may be very large.

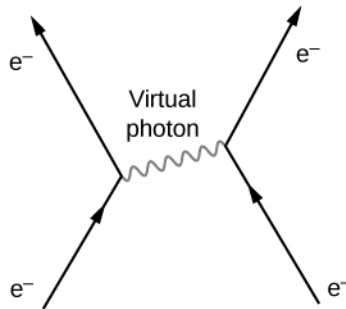


Figure 11.13 Feynman diagram of two electrons interacting through the exchange of a photon.

To estimate the range of the electromagnetic interaction, assume that the uncertainty on the energy is comparable to the energy of the photon itself, written

$$\Delta E \approx E. \quad (11.4)$$

The Heisenberg uncertainty principle states that

$$\Delta E \approx \frac{h}{\Delta t}. \quad (11.5)$$

Combining these equations, we have

$$\Delta t \approx \frac{h}{E}. \quad (11.6)$$

The energy of a photon is given by $E = hf$, so

$$\Delta t \approx \frac{h}{hf} \approx \frac{1}{f} = \frac{\lambda}{c}. \quad (11.7)$$

The distance d that the photon can move in this time is therefore

$$d = c \Delta t \approx c \left(\frac{\lambda}{c} \right) = \lambda. \quad (11.8)$$

The energy of the virtual photon can be arbitrarily small, so its wavelength can be arbitrarily large—in principle, even infinitely large. The electromagnetic force is therefore a long-range force.

Weak Nuclear Force

The weak nuclear force is responsible for radioactive decay. The range of the weak nuclear force is very short (only about 10^{-18} m) and like the other forces in the Standard Model, the weak force can be described in terms of particle exchange. (There is no simple function like the Coulomb force to describe these interactions.) The particle exchanged is one of three bosons: W^+ , W^- , and Z^0 . The Standard Model predicts the existence of these spin-1 particles and also predicts their specific masses. In combination with previous experiments, the mass of the charged W bosons was predicted to be $81 \text{ GeV}/c^2$ and that of the Z^0 was predicted to be $90 \text{ GeV}/c^2$. A CERN experiment discovered particles in the 1980s with precisely these masses—an impressive victory for the model.

The weak nuclear force is most frequently associated with scattering and decays of unstable particles to light particles. For example, neutrons decay to protons through the weak nuclear force. This reaction is written

$$n \rightarrow p + e^- + \nu_e,$$

where n is the neutron, p is a proton, e^- is an electron, and ν_e is a nearly massless electron neutrino. This process, called beta decay, is important in many physical processes. A Feynman diagram of beta decay is given in **Figure 11.14(a)**. The neutron emits a W^- and becomes a proton, then the W^- produces an electron and an antineutrino. This process is similar to the scattering event

$$e^- + p \rightarrow n + \nu_e,$$

In this process, the proton emits a W^+ and is converted into a neutron (b). The W^+ then combines with the electron, forming a neutrino. Other electroweak interactions are considered in the exercises.

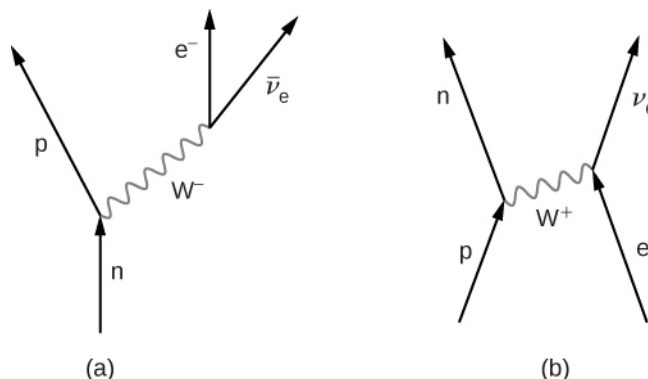


Figure 11.14 Feynman diagram of particles interacting through the exchange of a W boson: (a) beta decay; (b) conversion of a proton into a neutron.

The range of the weak nuclear force can be estimated with an argument similar to the one before. Assuming the uncertainty on the energy is comparable to the energy of the exchange particle by ($E \approx mc^2$), we have

$$\Delta t \approx \frac{h}{mc^2}. \quad (11.9)$$

The maximum distance d that the exchange particle can travel (assuming it moves at a speed close to c) is therefore

$$d \approx c\Delta t = \frac{h}{mc}. \quad (11.10)$$

For one of the charged vector bosons with $mc^2 \approx 80 \text{ GeV} = 1.28 \times 10^{-8} \text{ J}$, we obtain $mc = 4.27 \times 10^{-17} \text{ J} \cdot \text{s/m}$. Hence, the range of the force mediated by this boson is

$$d \approx \frac{1.05 \times 10^{-34} \text{ J} \cdot \text{s}}{4.27 \times 10^{-17} \text{ J} \cdot \text{s/m}} \approx 2 \times 10^{-18} \text{ m}. \quad (11.11)$$

Strong Nuclear Force

Strong nuclear interactions describe interactions between quarks. Details of these interactions are described by QCD. According to this theory, quarks bind together by sending and receiving gluons. Just as quarks carry electric charge [either $(+2/3)e$ or $(-1/3)e$] that determines the strength of electromagnetic interactions between the quarks, quarks also carry “color charge” (either red, blue, or green) that determines the strength of strong nuclear interactions. As discussed before, quarks bind together in groups in color neutral (or “white”) combinations, such as red-blue-green and red-antired.

Interestingly, the gluons themselves carry color charge. Eight known gluons exist: six that carry a color and anticolor, and two that are color neutral (**Figure 11.15(a)**). To illustrate the interaction between quarks through the exchange of charged gluons, consider the Feynman diagram in part (b). As time increases, a red down quark moves right and a green strange quark moves left. (These appear at the lower edge of the graph.) The up quark exchanges a red-antigreen gluon with the strange quark. (Anticolors are shown as secondary colors. For example, antired is represented by cyan because cyan mixes with red to form white light.) According to QCD, all interactions in this process—identified with the vertices—must be color neutral. Therefore, the down quark transforms from red to green, and the strange quark transforms from green to red.

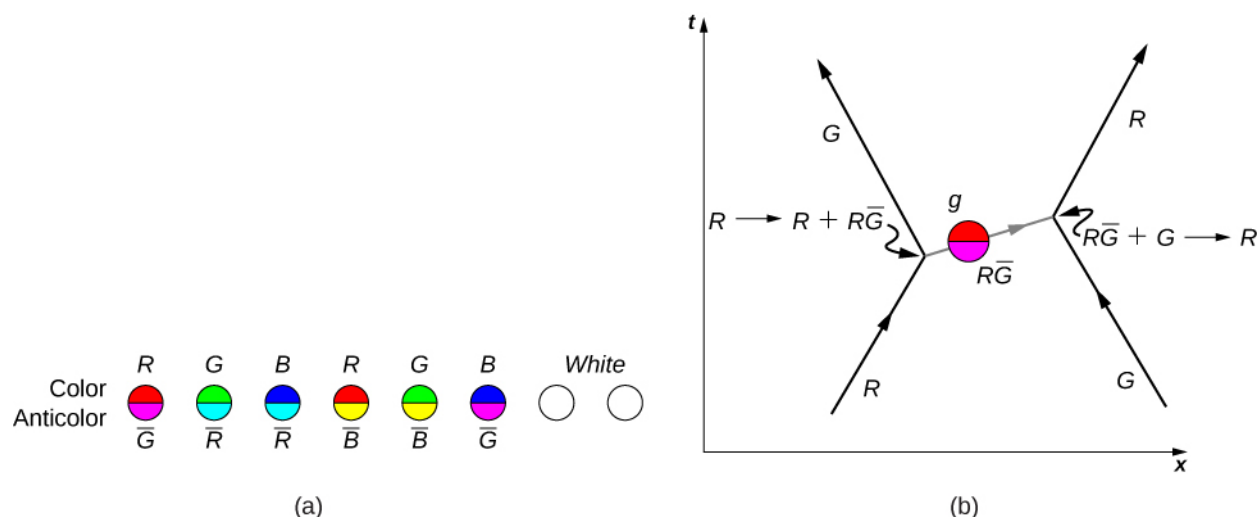


Figure 11.15 (a) Eight types of gluons carry the strong nuclear force. The white gluons are mixtures of color-anticolor pairs. (b) An interaction between two quarks through the exchange of a gluon.

As suggested by this example, the interaction between quarks in an atomic nucleus can be very complicated. **Figure 11.16** shows the interaction between a proton and neutron. Notice that the proton converts into a neutron and the neutron converts into a proton during the interaction. The presence of quark-antiquark pairs in the exchange suggest that bonding between nucleons can be modeled as an exchange of pions.

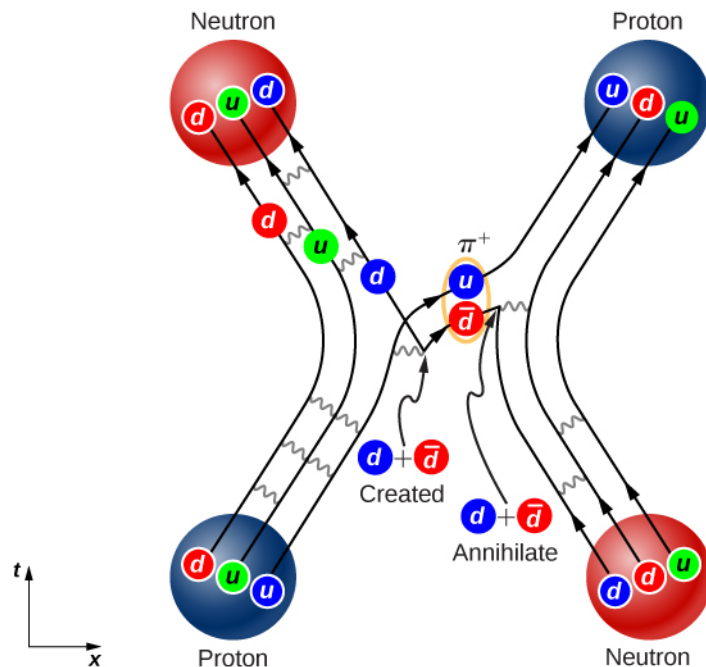


Figure 11.16 A Feynman diagram that describes a strong nuclear interaction between a proton and a neutron.

In practice, QCD predictions are difficult to produce. This difficulty arises from the inherent strength of the force and the inability to neglect terms in the equations. Thus, QCD calculations are often performed with the aid of supercomputers. The existence of gluons is supported by electron-nucleon scattering experiments. The estimated quark momenta implied by these scattering events are much smaller than we would expect without gluons because the gluons carry away some of the momentum of each collision.

Unification Theories

Physicists have long known that the strength of an interaction between particles depends on the distance of the interaction.

For example, two positively charged particles experience a larger repulsive force at a short distance than at a long distance. In scattering experiments, the strength of an interaction depends on the energy of the interacting particle, since larger energy implies both closer and stronger interactions.

Particle physicists now suspect that the strength of all particle interactions (the four forces) merge at high energies, and the details of particle interactions at these energies can be described in terms of a single force (**Figure 11.17**). A unified theory describes what these interactions are like and explains why this description breaks down at low-energy scales. A grand unified theory is a theory that attempts to describe strong and electroweak interaction in terms of just one force. A theory of everything (TOE) takes the unification concept one step further. A TOE combines all four fundamental forces (including gravity) into one theory.

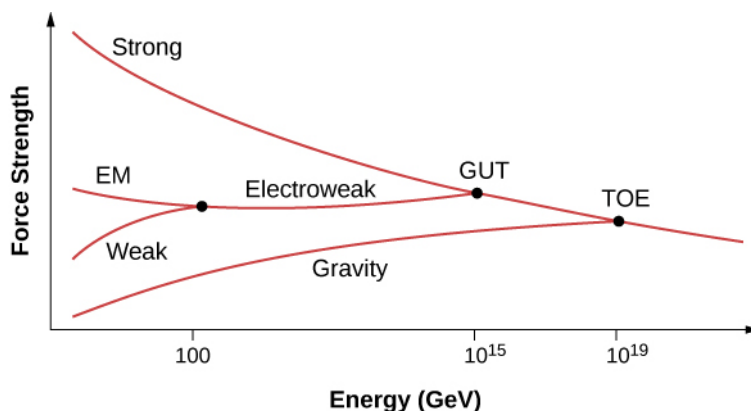


Figure 11.17 Grand unification of forces at high energies.

11.6 | The Big Bang

Learning Objectives

By the end of this section, you will be able to:

- Explain the expansion of the universe in terms of a Hubble graph and cosmological redshift
- Describe the analogy between cosmological expansion and an expanding balloon
- Use Hubble's law to make predictions about the measured speed of distant galaxies

We have been discussing elementary particles, which are some of the smallest things we can study. Now we are going to examine what we know about the universe, which is the biggest thing we can study. The link between these two topics is high energy: The study of particle interactions requires very high energies, and the highest energies we know about existed during the early evolution of the universe. Some physicists think that the unified force theories we described in the preceding section may actually have governed the behavior of the universe in its earliest moments.

Hubble's Law

In 1929, Edwin Hubble published one of the most important discoveries in modern astronomy. Hubble discovered that (1) galaxies appear to move away from Earth and (2) the velocity of recession (v) is proportional to the distance (d) of the galaxy from Earth. Both v and d can be determined using stellar light spectra. A best fit to the sample illustrative data is given in **Figure 11.18**. (Hubble's original plot had a considerable scatter but a general trend was still evident.)