23.3 The Unification of Forces

Section Learning Objectives

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

- Define a grand unified theory and its importance
- Explain the evolution of the four fundamental forces from the Big Bang onward
- Explain how grand unification theories can be tested

Section Key Terms

Big Bang	Electroweak Epoch	electroweak theory	Grand Unification Epoch	Grand Unified Theory
Inflationary Epoch	Planck Epoch	Quark Era	superforce	Theory of Everything

Understanding the Grand Unified Theory

Present quests to show that the four basic forces are different manifestations of a single unified force that follow a long tradition. In the nineteenth century, the distinct electric and magnetic forces were shown to be intimately connected and are now collectively called the electromagnetic force. More recently, the weak nuclear force was united with the electromagnetic force. As shown in Figure 23.19, carrier particles transmit three of the four fundamental forces in very similar ways. With these considerations in mind, it is natural to suggest that a theory may be constructed in which the strong nuclear, weak nuclear, and electromagnetic forces are all unified. The search for a correct theory linking the forces, called the **Grand Unified Theory (GUT)**, is explored in this section.

In the 1960s, the **electroweak theory** was developed by Steven Weinberg, Sheldon Glashow, and Abdus Salam. This theory proposed that the electromagnetic and weak nuclear forces are identical at sufficiently high energies. At lower energies, like those in our present-day universe, the two forces remain united but manifest themselves in different ways. One of the main consequences of the electroweak theory was the prediction of three short-range carrier particles, now known as the W^+, W^-, and Z^0 bosons. Not only were three particles predicted, but the mass of each W^+ and W^- boson was predicted to be 81 GeV/c^2, and that of the Z^0 boson was predicted to be 90 GeV/c^2. In 1983, these carrier particles were observed at CERN with the predicted characteristics, including masses having those predicted values as given in .

How can forces be unified? They are definitely distinct under most circumstances. For example, they are carried by different particles and have greatly different strengths. But experiments show that at extremely short distances and at extremely high energies, the strengths of the forces begin to become more similar, as seen in Figure 23.20.

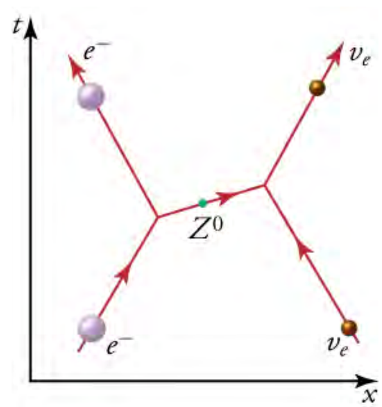


Figure 23.19 The exchange of a virtual Z^0 particle (boson) carries the weak nuclear force between an electron and a neutrino in this Feynman diagram. This diagram is similar to the diagrams in Figure 23.6 and for the electromagnetic and strong nuclear forces.

As discussed earlier, the short ranges and large masses of the weak carrier bosons require correspondingly high energies to create them. Thus, the energy scale on the horizontal axis of Figure 23.20 also corresponds to shorter and shorter distances (going from left to right), with 100 GeV corresponding to approximately 10^{-18} m, for example. At that distance, the strengths of the electromagnetic and weak nuclear forces are the same. To test this, energies of about 100 GeV are put into the system. When this occurs, the W^+, W^-, and Z^0 carrier particles are created and released. At those and higher energies, the masses of the carrier particles become less and less relevant, and the Z^0 boson in particular resembles the massless, chargeless photon. As further energy is added, the W^+, W^-, and Z^0 particles are further transformed into massless carrier particles even more similar to photons and gluons.

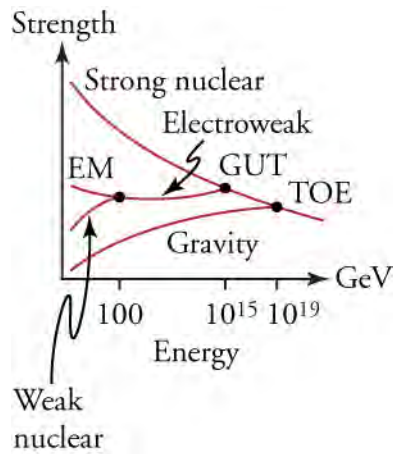


Figure 23.20 The relative strengths of the four basic forces vary with distance, and, hence, energy is needed to probe small distances. At ordinary energies (a few eV or less), the forces differ greatly. However, at energies available in accelerators, the weak nuclear and electromagnetic (EM) forces become unified. Unfortunately, the energies at which the strong nuclear and electroweak forces become the same are unreachable in any conceivable accelerator. The universe may provide a laboratory, and nature may show effects at ordinary energies that give us clues about the validity of this graph.

The extremely short distances and high energies at which the electroweak force becomes identical with the strong nuclear force are not reachable with any conceivable human-built accelerator. At energies of about 10^{14} GeV (16,000 J per particle), distances of about 10 to 30 m can be probed. Such energies are needed to test the theory directly, but these are about 10^{10} times higher than the maximum energy associated with the LHC, and the distances are about 10 to 12 smaller than any structure we have direct knowledge of. This would be the realm of various GUTs, of which there are many, since there is no constraining evidence at these energies and distances. Past experience has shown that anytime you probe so many orders of magnitude further, you find the unexpected.

While direct evidence of a GUT is not presently possible, that does not rule out the ability to assess a GUT through an indirect process. Current GUTs require various other events as a consequence of their theory. Some GUTs require the existence of magnetic monopoles, very massive individual north- and south-pole particles, which have not yet been proven to exist, while others require the use of extra dimensions. However, not all theories result in the same consequences. For example, disproving the existence of magnetic monopoles will not disprove all GUTs. Much of the science we accept in our everyday lives is based on different models, each with their own strengths and limitations. Although a particular model may have drawbacks, that does not necessarily mean that it should be discounted completely.

One consequence of GUTs that can theoretically be assessed is proton decay. Multiple current GUTs hypothesize that the stable proton should actually decay at a lifetime of 10^{31} years. While this time is incredibly large (keep in mind that the age of the universe is less than 14 billion years), scientists at the Super-Kamiokande in Japan have used a 50,000-ton tank of water to search for its existence. The decay of a single proton in the Super-Kamiokande tank would be observed by a detector, thereby providing support for the predicting GUT model. However, as of 2014, 17 years into the experiment, decay is yet to be found. This time span equates to a minimum limit on proton life of 5.9×10^{33} years. While this result certainly does not support many grand unifying theories, an acceptable model may still exist.

TIPS FOR SUCCESS

The Super-Kamiokande experiment is a clever use of proportional reasoning. Because it is not feasible to test for 10^{31} years in order for a single proton to decay, scientists chose instead to manipulate the proton–time ratio. If one proton decays in 10^{31}

years, then in one year 10^{-31} protons will decay. With this in mind, if scientists wanted to test the proton decay theory in one year, they would need 10^{31} protons. While this is also unfeasible, the use of a 50,000-ton tank of water helps to bring both the wait time and proton number to within reason.

The Standard Model and the Big Bang

Nature is full of examples where the macroscopic and microscopic worlds intertwine. Newton realized that the nature of gravity on Earth that pulls an apple to the ground could explain the motion of the moon and planets so much farther away. Decays of tiny nuclei explain the hot interior of the Earth. Fusion of nuclei likewise explains the energy of stars. Today, the patterns in particle physics seem to be explaining the evolution and character of the universe. And the nature of the universe has implications for unexplored regions of particle physics.

In 1929, Edwin Hubble observed that all but the closest galaxies surrounding our own had a red shift in their hydrogen spectra that was proportional to their distance from us. Applying the Doppler Effect, Hubble recognized that this meant that all galaxies were receding from our own, with those farther away receding even faster. Knowing that our place in the universe was no more unique than any other, the implication was clear: The space within the universe itself was expanding. Just like pen marks on an expanding balloon, everything in the universe was accelerating away from everything else.

Figure 23.21 shows how the recession of galaxies looks like the remnants of a gigantic explosion, the famous **Big Bang**. Extrapolating backward in time, the Big Bang would have occurred between 13 and 15 billion years ago, when all matter would have been at a single point. From this, questions instantly arise. What caused the explosion? What happened before the Big Bang? Was there a before, or did time start then? For our purposes, the biggest question relating to the Big Bang is this: How does the Big Bang relate to the unification of the fundamental forces?

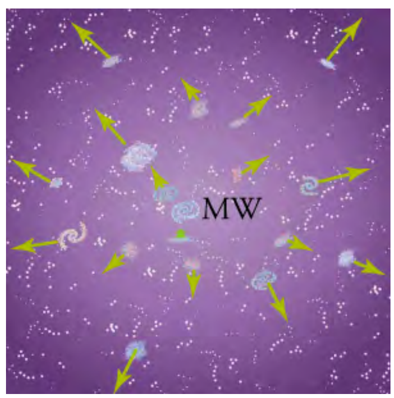


Figure 23.21 Galaxies are flying apart from one another, with the more distant ones moving faster, as if a primordial explosion expelled the matter from which they formed. The most distant known galaxies move nearly at the speed of light relative to us.

To fully understand the conditions of the very early universe, recognize that as the universe contracts to the size of the Big Bang, changes will occur. The density and temperature of the universe will increase dramatically. As particles become closer together, they will become too close to exist as we know them. The high energies will create other, more unusual particles to exist in greater abundance. Knowing this, let's move forward from the start of the universe, beginning with the Big Bang, as illustrated in Figure 23.22.

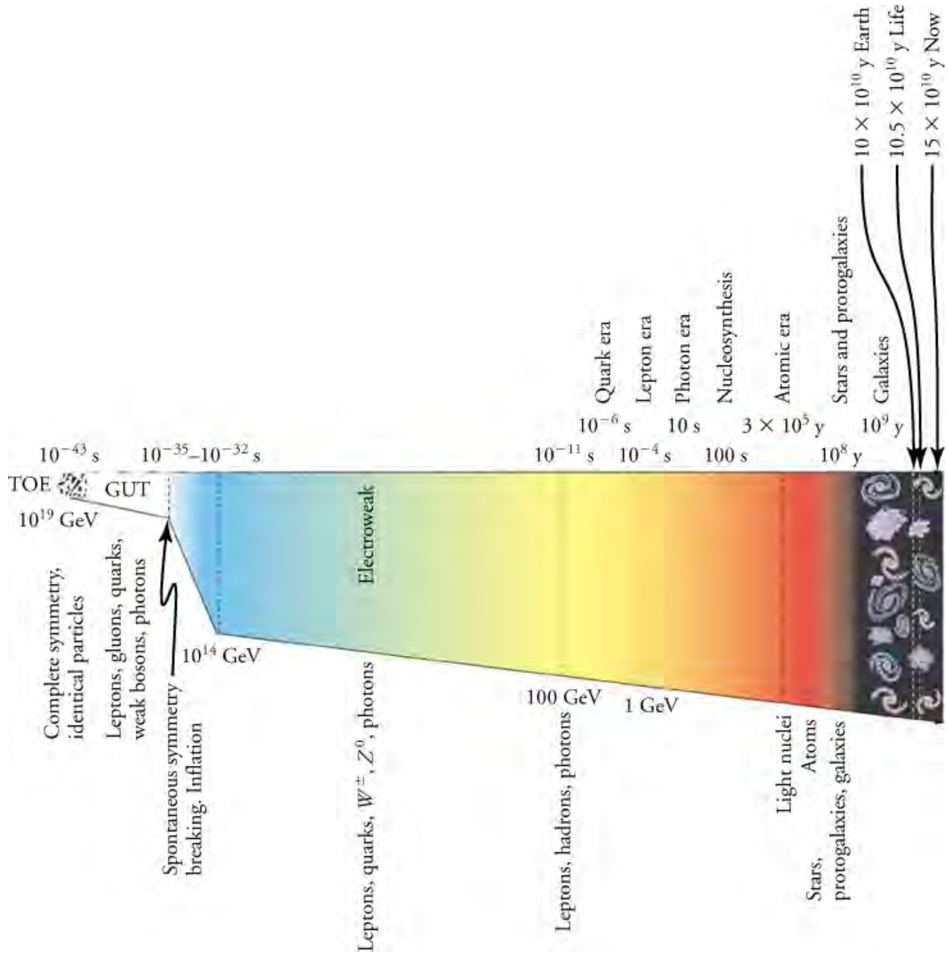


Figure 23.22 The evolution of the universe from the Big Bang onward (from left to right) is intimately tied to the laws of physics, especially those of particle physics at the earliest stages. Theories of the unification of forces at high energies may be verified by their shaping of the universe and its evolution.

The **Planck Epoch** $\left(0 \rightarrow 10^{-43}\text{ s}\right)$ —Though scientists are unable to model the conditions of the Planck Epoch in the laboratory, speculation is that at this time compressed energy was great enough to reach the immense 10^{19} GeV necessary to unify gravity with all other forces. As a result, modern cosmology suggests that all four forces would have existed as one force, a hypothetical **superforce** as suggested by the **Theory of Everything**.

The **Grand Unification Epoch** $\left(10^{-43} \rightarrow 10^{-36}\text{ s}\right)$ —As the universe expands, the temperatures necessary to maintain the superforce decrease. As a result, gravity separates, leaving the electroweak and strong nuclear forces together. At this time, the electromagnetic, weak, and strong forces are identical, matching the conditions requested in the Grand Unification Theory.

The **Inflationary Epoch** $\left(10^{-36} \rightarrow 10^{-32}\text{ s}\right)$ —The separation of the strong nuclear force from the electroweak force during this time is thought to have been responsible for the massive inflation of the universe. Corresponding to the steep diagonal line on the left side of Figure 23.22, the universe may have expanded by a factor of 10^{50} or more in size. In fact, the expansion was so great during this time that it actually occurred faster than the speed of light! Unfortunately, there is little hope that we may be able to test the inflationary scenario directly since it occurs at energies near 10^{14} GeV, vastly greater than the limits of modern accelerators.

The **Electroweak Epoch** $\left(10^{-32} \rightarrow 10^{-11}\text{ s}\right)$ —Now separated from both gravity and the strong nuclear force, the electroweak force exists as a singular force during this time period. As stated earlier, scientists are able to create the energies at this stage in the universe's expansion, needing only 100 GeV, as shown in Figure 23.20. W and Z bosons, as well as the Higgs boson, are released during this time.

The **Quark Era** $\left(10^{-11} \rightarrow 10^{-6}\text{ s}\right)$ —During the Quark Era, the universe has expanded and temperatures have decreased to the point at which all four fundamental forces have separated. Additionally, quarks began to take form as energies decreased.

As the universe expanded, further eras took place, allowing for the existence of hadrons, leptons, and photons, the fundamental particles of the standard model. Eventually, in nucleosynthesis, nuclei would be able to form, and the basic building blocks of atomic matter could take place. Using particle accelerators, we are very much working backwards in an attempt to understand the universe. It is encouraging to see that the macroscopic conditions of the Big Bang align nicely with our submicroscopic particle theory.

Check Your Understanding

19. Is there one grand unified theory or multiple grand unifying theories?
   a. one grand unifying theory
   b. multiple grand unifying theories

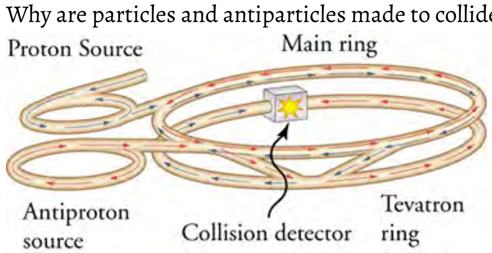
20. In what manner is $E = mc^2$ considered a precursor to the Grand Unified Theory?
   a. The grand unified theory seeks relate the electroweak and strong nuclear forces to one another just as $E = mc^2$ related energy and mass.
   b. The grand unified theory seeks to relate the electroweak force and mass to one another just as $E = mc^2$ related energy and mass.
   c. The grand unified theory seeks to relate the mass and strong nuclear forces to one another just as $E = mc^2$ related energy and mass.
   d. The grand unified theory seeks to relate gravity and strong nuclear force to one another, just as $E = mc^2$ related energy and mass.

21. List the following eras in order of occurrence from the Big Bang: Electroweak Epoch, Grand Unification Epoch, Inflationary Epoch, Planck Epoch, Quark Era.
   a. Quark Era, Grand Unification Epoch, Inflationary Epoch, Electroweak Epoch, Planck Epoch
   b. Planck Epoch, Inflationary Epoch, Grand Unification Epoch, Electroweak Epoch, Quark Era
   c. Planck Epoch, Electroweak Epoch, Grand Unification Epoch, Inflationary Epoch, Quark Era
   d. Planck Epoch, Grand Unification Epoch, Inflationary Epoch, Electroweak Epoch, Quark Era

22. How did the temperature of the universe change as it expanded?
   a. The temperature of the universe increased.
   b. The temperature of the universe decreased.
   c. The temperature of the universe first decreased and then increased.
   d. The temperature of the universe first increased and then decreased.

23. Under current conditions, is it possible for scientists to use particle accelerators to verify the Grand Unified Theory?
   a. No, there is not enough energy.
   b. Yes, there is enough energy.

24. Why are particles and antiparticles made to collide as shown in this image?



   a. Particles and antiparticles have the same mass.
   b. Particles and antiparticles have different mass.
   c. Particles and antiparticles have the same charge.
   d. Particles and antiparticles have opposite charges.

25. The existence of what particles were predicted as a consequence of the electroweak theory?
   a. fermions
   b. Higgs bosons

c. leptons
d. W^+, W^-, and Z° bosons