14
The Very Early Universe

At the time of nucleosynthesis, the primordial fireball consisted of electrons, protons, neutrons, photons and neutrinos. As we get closer to the big bang, the fireball gets hotter and denser, and other types of particles emerge. They move at nearly the speed of light, colliding frequently and violently. As we shall see, some of the most dramatic events in the history of the universe occurred within a small fraction of a second after the big bang.

14.1 Particle Physics and the Big Bang

The density and temperature of the universe increase as we follow their evolution backward in time, towards the big bang. If time is measured in seconds, then the density and temperature are given by[1]

$$\rho \approx \frac{4.5 \times 10^8}{t^2}\ \mathrm{kg/m^3} \tag{14.1}$$

and

$$T \approx \frac{10^{10}}{\sqrt{t}}\ \mathrm{K} \tag{14.2}$$

[1]These relations hold during the *radiation era*. While we won't derive these equations here (see the Appendix), we will outline how the dependence on time emerges. The energy density is proportional to the inverse fourth power of the scale factor, $\rho \propto a(t)^{-4}$; the temperature scales as the inverse scale factor, $T \propto a(t)^{-1}$; and the scale factor is proportional to the square root of time, $a(t) \propto \sqrt{t}$ (found by solving Friedman's equation during the radiation era). Thus, $\rho \propto t^{-2}$, and $T \propto t^{-\frac{1}{2}}$.

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The temperature of the early universe is proportional to the average photon energy. Physicists measure particle energies and masses in electron-volts. One electron-volt is the energy gained by an electron as it moves across a potential difference of one volt, $1\,\text{eV} = 1.6 \times 10^{-19}$ J; the equivalent mass is $1\,\text{eV} = 2 \times 10^{-36}$ kg. Other related units are the $\text{MeV} = 10^6$ eV, $\text{GeV} = 10^9$ eV, and $\text{TeV} = 10^{12}$ eV. If energy is measured in MeV and temperature in Kelvins, the average energy per photon is roughly

$$E \sim 10^{-10} T \text{ MeV}. \tag{14.3}$$

Thus, an energy of $E = 1$ MeV corresponds to a temperature of $T \sim 10^{10}$ K.

It follows from Eqs. (14.1) and (14.2) that at about 100 s (when nucleosynthesis takes place), the density of the universe is about 50 times that of water ($\rho = 50{,}000$ kg/m^3), and the temperature is a billion Kelvin ($T = 10^9$ K), which is about 100 times hotter than the core of the Sun. At 1 s, the density is 500 thousand times that of water, and the temperature is 10 billion Kelvin. Jumping back to a microsecond, the density soars to $\rho \sim 10^{21}$ kg/m^3, and the temperature is ten trillion Kelvin ($T = 10^{13}$ K). The primordial cauldron is an extreme environment! The closer we get to the big bang, the more energetic the particles become and the more frequently they smash into one another. It is therefore important to understand what happens in such high-energy collisions.

Physicists study particle collisions with the help of colossal machines called accelerators. Inside an accelerator particle accelerator, particles are boosted to extremely high energies by electric fields, and then oppositely directed particle beams are aimed at one another in a small area surrounded by detectors. By studying the collision debris, physicists try to figure out the laws governing high-energy particle interactions (Fig. 14.1).

In a high-energy particle collision, there are generally a number of possible outcomes, which occur with different probabilities. The range of possibilities is restricted by a few *conservation laws*, such as energy and charge conservation: the total energy and the total electric charge should be the same before and after the collision. Other conserved quantities include baryon and lepton numbers and the "color" charge. Any process that is not forbidden by conservation laws will occur with some nonzero probability, which can be calculated using the rules of quantum mechanics.

A remarkable property of particle encounters is that the colliding particles can change their identity. For example, a pair of photons can turn into an electron-positron pair, as illustrated in Fig. 14.2. The positron is the electron's antiparticle—all particles have an antiparticle with identical properties, except for having opposite charges. Photons are their own antiparticles;

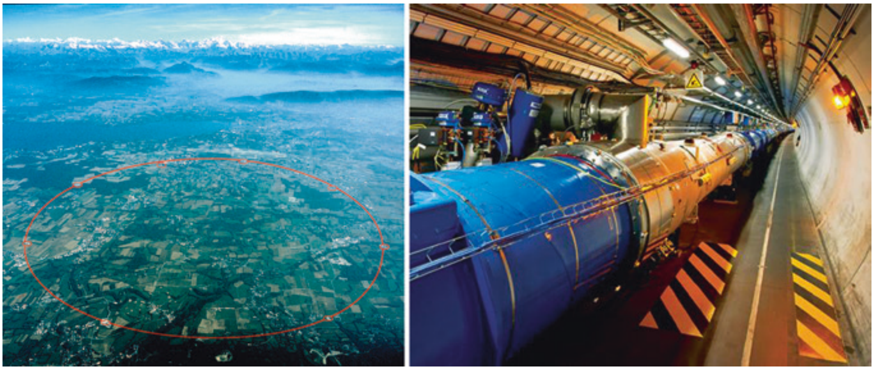

Fig. 14.1 The Large Hadron Collider (LHC) in Geneva Switzerland lies underground in a circular tunnel with a circumference of nearly 30 km. It is the largest particle accelerator in the world. The LHC achieves energies of $E = 14$ TeV, which correspond to temperatures of $T = 10^{17}$ K and a time of $t = 10^{-14}$ s after the big bang *Credit* CERN

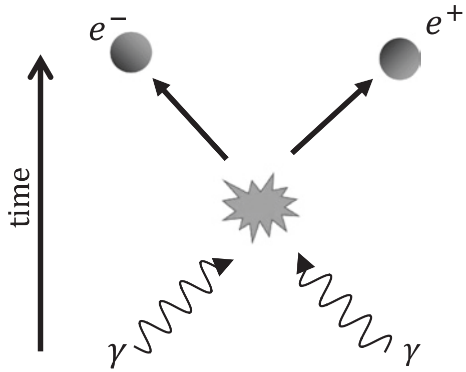

Fig. 14.2 Two photons collide to produce an electron-positron pair

their electric and other charges are all equal to zero. Particles and antiparticles are often created in pairs, as in the electron-positron pair production. The inverse process, called pair annihilation occurs when a particle and an antiparticle collide and turn into two photons. The number of particles can also be changed: two initial particles can produce a hail of other particles flying away from the collision point (see Fig. 14.3). These types of events were commonplace in the early moments after the big bang.

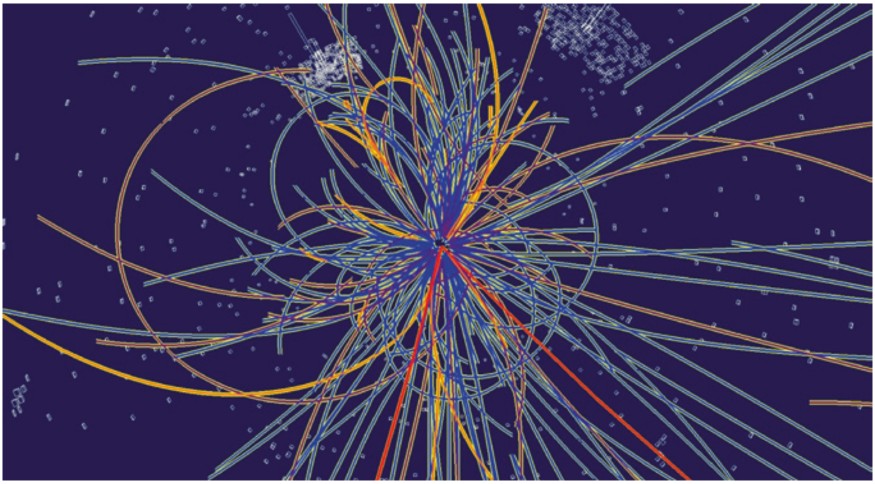

Fig. 14.3 A multitude of particles is produced in a proton-proton collision. The trajectories of positively and negatively charged particles are curved by magnetic fields, resulting in the circular paths

Energy conservation requires that a pair of photons creating a particle-antiparticle pair must have a combined energy of at least 2 mc^2, where m is the particle's mass.[2] The electron mass is $m_e \approx 0.5$ MeV, so electron-positron pairs are copiously produced at temperatures greater than 5×10^9 K (corresponding to photon energies $E \gtrsim 0.5$ MeV). As a result, the primordial fireball gets populated with electrons and positrons having about the same density as photons, and about the same energy per particle. Under these conditions, pair creation by photon collisions occurs at the same rate as pair annihilation due to electron-positron encounters, so electrons, positrons and photons are in thermal equilibrium.

At still higher temperatures, more massive particles and antiparticles appear. Muons, for example, have a mass of $m_\mu \approx 100$ MeV; in the first microsecond they are abundantly present in equilibrium with their antiparticles, at $T > 10^{12}$ K. Each kind of particle has a threshold temperature that must be reached in order for that particle type to be created in large numbers. In the early universe, as the fireball expands and cools, particles and antiparticles annihilate, and cannot be replenished, when the temperature drops below the corresponding threshold. Thus, muons annihilate with antimuons at $t \sim 10^{-6}$ s, and electron-positron pairs annihilate at $t \sim 1$ s ABB.

[2]When we say a particle has mass m, we usually refer to its rest mass.

14.2 The Standard Model of Particle Physics

Particle physicists have developed a theory, called the Standard Model, which accurately describes most of the known particles and their interactions (see Fig. 14.4). Particles can be divided into *matter* particles called fermions, and force particles, called *gauge bosons*. In addition, there is a particle called the Higgs boson, which plays a special role in the theory, as we shall explain below.

Technically, the classification of particles into fermions and bosons is based on a quantum property called spin. Very roughly, a particle can be pictured as a tiny ball rotating about its axis, with spin characterizing the intensity of rotation. Spin can take only a discrete set of values: 0, 1/2, 1, 3/2, …. Fermions have half- integer spin, and bosons have integer spin. All fermions of the Standard Model have spin ½, all gauge bosons have spin 1, and the Higgs boson has spin 0.

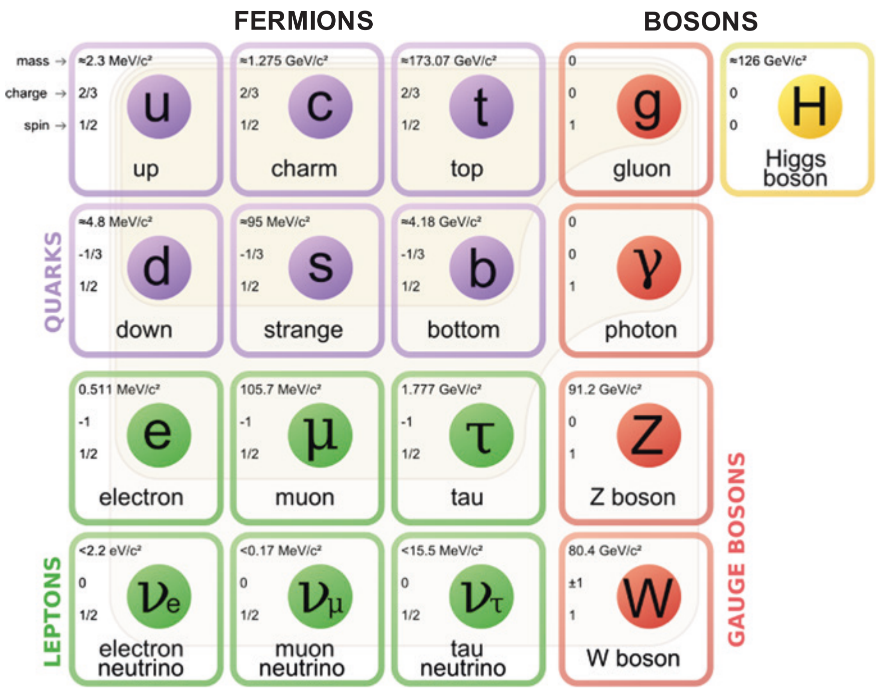

Fig. 14.4 The particles of the Standard Model, including their mass, electric charge and spin

14.2.1 The Particles

The elementary fermions include six quarks (with the whimsical names[3]: up, down, charm, strange, top and bottom) and six leptons (the electron, muon, tau particle, and their associated neutrinos). Individual quarks are never observed in nature; they are always tightly bound together into composite particles called hadrons. The most familiar hadrons are protons (composed of two up and one down quarks) and neutrons (composed of one up and two down quarks). All other hadrons are unstable. They can be produced in particle accelerators, but thereafter decay in a small fraction of a second. Leptons do not bind together like quarks do. All three neutrinos are stable, very light, and interact extremely weakly. The muon and the tau have the same electric charge as the electron, but are much heavier and rapidly decay into electrons and neutrinos.

To describe almost all known matter, we need essentially only four particles: the up and down quarks, the electron and the electron neutrino. Together they make up the so-called first generation of elementary particles. Apart from accelerator experiments and some extreme astrophysical processes, the properties of our world would not change if the other two generations (the second and third columns in Fig. 14.4) did not exist.

14.2.2 The Forces

All the interactions between particles can be described by four forces: gravity, electromagnetism, the weak nuclear force and the strong nuclear force. Although we are all very familiar with gravity, it is the only force (that we know of) that is not described by the Standard Model of particle physics—we will return to this important distinction later. All particles interact gravitationally via the hypothesized graviton, which has yet to be observed.

The electromagnetic force acts between electrically charged particles. It is mediated by photons: one particle emits a photon and the other absorbs it, as shown in Fig. 14.5. This force gives rise to most of the physics we are familiar with, and to all of chemistry. It is the glue that keeps electrons in atoms and is responsible for interactions between atoms and molecules.

As its name suggests, the strong nuclear force is the strongest of the four interactions. It binds quarks into nucleons and holds nucleons together

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[3]The quark names have no meaning other than serving to distinguish the different quark particles. For example, "up" and "down" have nothing to do with direction.

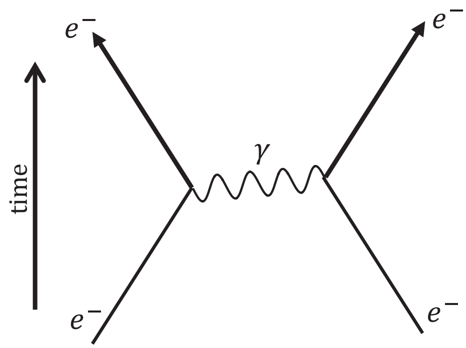

Fig. 14.5 Two electrons are electromagnetically repelled as they exchange a photon

in nuclei. Quarks carry the so-called "color" charge and interact through exchange of gluons, in much the same way as electrically charged particles interact through the exchange of photons. An important difference is that photons carry no electric charge while gluons themselves carry a color charge and can emit and absorb other gluons.

The weak nuclear force is responsible for some radioactive decays and for the interactions of neutrinos. It is mediated by the massive W and Z bosons. The weakness of this interaction and its short (microscopic) range are due to the large masses of its gauge bosons.

The Higgs boson does not mediate any force, but this particle and its associated field, called the Higgs field, play a key role in the Standard Model. The Higgs field is related to the Higgs particle in the same way as the electromagnetic field is related to the photon. The Higgs boson has a large mass and a short lifetime; its production requires very powerful accelerators. It was finally discovered in 2012, almost 50 years after its prediction in 1964 by Peter Higgs and by Francois Englert and Robert Brout. The Higgs field is present all around us, at every point in space, and its presence has a dramatic impact on the physical character of our world.

To illustrate the properties and the significance of the Higgs field, we can compare it to the magnetic field, which also permeates the space around us. We cannot feel the magnetic field with our sense organs, but we can detect its presence using a compass or by observing trajectories of charged particles;

instead of a straight line, a particle in a magnetic field moves along a spiral path.[4] Magnetic fields are produced by electric currents; for example, the magnetic field of the Earth is due to the currents flowing in the core of our planet. But as one gets very far away from planets and stars, the magnetic field strength declines towards zero.

The Higgs field, on the other hand, is non-zero even in vacuum; it has the same strength everywhere in the universe. Another distinction is that the magnetic field is a vector—it is characterized by both magnitude and direction. The Higgs field is characterized only by its magnitude. Such fields are called *scalar fields*. In this regard the Higgs field is similar to the temperature, which also has some magnitude at each point in space and time, but no direction.

If we could vary the magnitude of the Higgs field, we would feel the unpleasant effects immediately. The masses of all matter particles in the Standard Model (except neutrinos) are proportional to the Higgs field. So, if the strength of the field were changed, the masses would also be altered, resulting in some new physical and chemical properties of all matter. If we could turn off the Higgs field completely, all Standard Model particles would become massless and would move at the speed of light. In particular, the W and Z bosons would be massless, like photons, and the weak nuclear force would be essentially indistinguishable from electromagnetism. The universe would be a very different place! So, why is the Higgs field non-zero?

14.3 Symmetry Breaking

There is a good reason why the magnetic field is zero in vacuum. Fields, like particles, have a certain amount of energy. In any region where the magnetic field is non-zero, it has an energy density proportional to the square of the field; see Fig. 14.6. As the field is increased, its energy grows. Since the vacuum is the state of lowest energy, the magnetic field must vanish in vacuum.

The energy density of the Higgs field exhibits a very different behavior, which is schematically illustrated in Fig. 14.7. The lowest energy states are now at non-zero values of the field, which are labeled V and $-\mathrm{V}$ in the figure. They are the vacuum states of the theory. It does not matter which of

[4]The spiral curves in opposite directions for positively and negatively charged particles, and its radius depends on the particle's energy. Physicists use these properties to analyze high-energy collisions, like the one shown in Fig. 14.3.

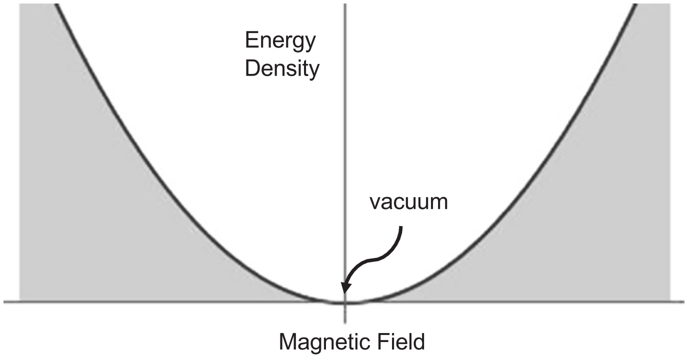

Fig. 14.6 Energy density of a magnetic field vs the magnitude of the field. When the field is zero, the energy density is also zero

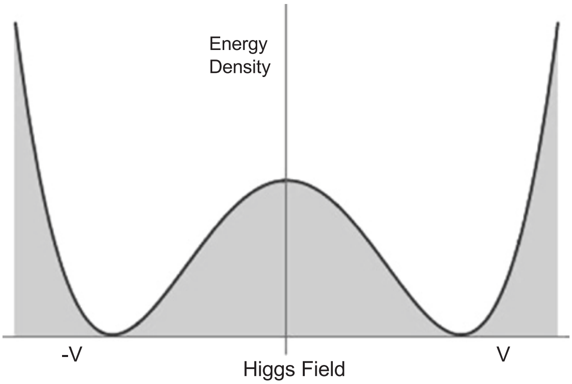

Fig. 14.7 Higgs field potential energy density. There are two vacuum states which have non-zero Higgs field values, labelled −V, and V

these states nature choses: they have identical physical properties. But with either choice the Higgs field is non-zero in the vacuum. The two vacuum states are separated by a high energy hill, with the top of the hill corresponding to vanishing Higgs field. Setting the Higgs field to zero, even in a small region of space, would thus be a very costly proposition. For just one cubic centimeter the required energy far exceeds the present energy resources of our planet.

The energy dependence of the kind shown in Fig. 14.7 is not uncommon in nature and can even occur for an ordinary magnetic field. The case in point is a simple bar magnet (Fig. 14.8). Each atom in a magnet acts like a tiny magnet itself. Interaction between these microscopic magnets causes them to align, resulting in a large magnetic field. The energy curve for a bar

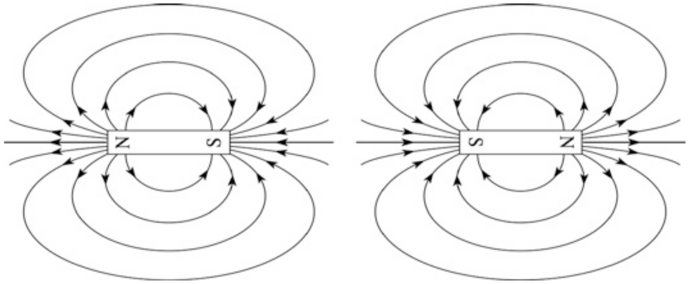

Fig. 14.8 The magnetic field of a bar magnet (*left*) and its rotated version about the vertical axis (*right*). The direction of magnetization reverses, but the energy is the same

magnet as a function of the magnetic field has the same form as in Fig. 14.7. The two energy minima now correspond to the same strength of the field, but opposite directions of magnetization. Clearly, these two states have identical properties, since they can be obtained from one another by rotating the magnet 180° about a vertical axis. In the case of a magnet, the energy cost of setting the magnetic field to zero is not prohibitively high. When the magnet is heated to a temperature above 10^3 K (the so-called Curie temperature), the alignment of atoms is destroyed by random thermal motions, and macroscopic magnetization disappears. If the magnet is then cooled below the Curie point, it gets spontaneously magnetized, with the direction of magnetization selected randomly by thermal fluctuations.[5]

We now introduce the important concepts of symmetry and symmetry breaking. We say that a physical system has symmetry if there are some transformations that leave it unchanged. For example, a spherical object is symmetric, since it does not change if we rotate it about any axis passing through its center. An iron bar heated above the Curie temperature has symmetry with respect to flipping. But the same bar below the Curie temperature has no such symmetry. It gets magnetized, and the magnetization direction is reversed when the bar is flipped. We say in such cases that the symmetry has been broken.

Getting back to the Standard Model, the state with a vanishing Higgs field has a high degree of symmetry. Matter particles in this state are

[5]This picture of spontaneous magnetization applies only to very small magnets. When a large piece of iron is cooled below the Curie temperature, it splits into a number of domains with different directions of magnetization.

interchangeable, since they all have zero mass.[6] The weak nuclear force is indistinguishable from electromagnetism; together, they are referred to as the electroweak force, and the symmetry between them is called the *electroweak symmetry.* As we discussed, however, this symmetric state does not correspond to the minimum of energy, so the Higgs field becomes non-zero and the symmetry gets broken.

Just like in a bar magnet, the electroweak symmetry is restored at sufficiently high temperatures. But in this case the universe has to be heated above 10^{15} K! The average particle energies are then $E > 100$ GeV, high enough to populate the fireball with *W*, *Z* and Higgs bosons. These extreme conditions are recreated in high-energy particle collisions. As predicted, experiments show that the differences between the weak and electromagnetic forces disappear at energies above 100 GeV.

14.4 The Early Universe Timeline

We are now ready to summarize the important milestones of the early universe.

Electroweak symmetry breaking: $t \sim 10^{-10}$ s ($T \sim 10^{15}$ K)
Before this event, all Standard Model particles are massless; they (and their antiparticles) populate the fireball with about the same density as photons. As the symmetry gets broken, all particle masses become different, and the weak and electromagnetic interactions become distinct. Soon after that, *W*, *Z* and Higgs bosons annihilate with their antiparticles.

Quark confinement: $t \sim 10^{-6}$ s ($T \sim 10^{13}$ K)
We mentioned in Sect. 14.2 that individual quarks are never observed; they are confined by gluons into protons and neutrons. However, at times earlier than a microsecond ABB, the density of protons, neutrons and their antiparticles is so high that they overlap, and their constituent quarks mix together, forming a dense gas of quarks, antiquarks and gluons. At $t \sim 10^{-6}$ s, the density of this gas drops enough for quarks to become bound together into non-overlapping protons and neutrons. The average particle energy at that time is $E \sim 1$ GeV. Almost all the protons, neutrons, and their antiparticles annihilate soon thereafter, producing photons (and also other light particles,

[6] More precisely, leptons cannot be distinguished from other leptons and quarks from other quarks, but quarks can be distinguished from leptons, since only quarks can interact through the exchange of gluons.

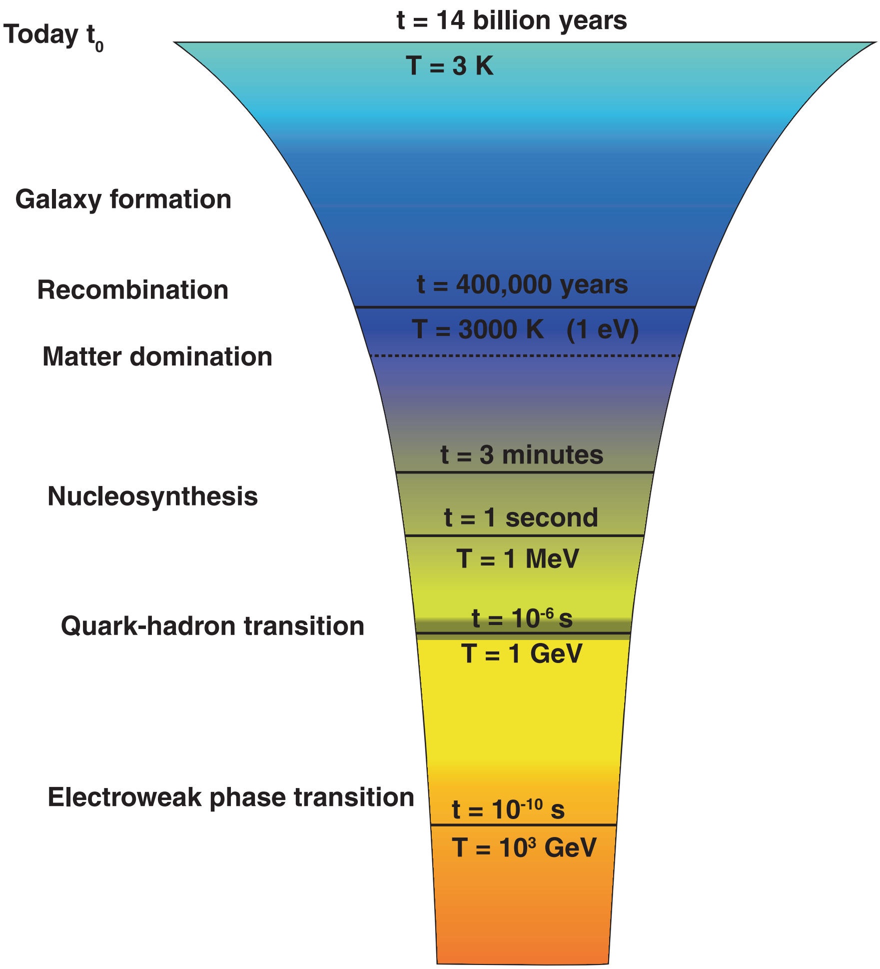

Fig. 14.9 Early universe timeline

like electrons, muons and neutrinos). But they could not all annihilate, since otherwise there would be no nucleons left to form atomic matter. This tells us that there was a small imbalance: nucleons outnumbered antinucleons by about one in a billion, so that the nucleon to photon ratio after the annihilation is $\frac{n_n}{n_\gamma} \sim 10^{-9}$. The surviving nucleons thus become the first bound systems that emerge as the universe cools.

Electron-positron annihilation: $t \sim 1$ s ($T \sim 10^{10}$ K)
Between 10^{-6} s and 1 s ABB, all remaining particle-antiparticle pairs disappear from the fireball. The last to disappear are the electron-positron pairs, which annihilate at $t \sim 1$ s. Like the case of nucleons and anti-nucleons,

there must have been a small excess ($\sim 10^{-9}$) of electrons over positrons, so that atomic matter could later be formed.

Nucleosynthesis: $t \sim 100$ **s** ($T \sim 10^9$ **K**)
Protons combine with neutrons that have not yet decayed to form helium and other light nuclei. The remaining protons exist freely as hydrogen nuclei.

Recombination: $t \sim 400{,}000$ ***yrs*** ($T \sim 3000$ **K**)
Nuclei are bound together with electrons to form neutral atoms. Photons of the fireball are now free to propagate through the neutral atomic gas and reach us in the form of cosmic microwave background radiation.

The timeline of the early universe is illustrated in Fig. 14.9, where we have also included some key events related to structure formation. Note that some of the most important events in the cosmic history occurred within the first second ABB.

14.5 Physics Beyond the Standard Model

The Standard Model describes much of the amazing variety and complexity of our physical world—and yet it is incomplete. It does not account for neutrino masses, and the gravitational force lies outside its scope. Moreover, as we discussed in Chap. 13, dark matter cannot be made of ordinary atoms and must consist of some unknown particles, not included in the Standard Model.

14.5.1 Unifying the Fundamental Forces

An overarching theme in the history of physics has been the idea of unification. It has long been a dream of particle physicists to develop a unified theory that describes all particles and their interactions. Einstein himself spent the last thirty years of his life, struggling (unsuccessfully) to unify electromagnetism with gravity.

In 1864, Maxwell's theory of electromagnetism unified the previously separate phenomena of electricity and magnetism. About 100 years later, scientists developed the *electroweak theory,*[7] which unified electromagnetism

[7] Steven Weinberg, Abdus Salam and Sheldon Glashow shared the 1979 Physics Nobel prize for this work.

and the weak interactions at energies $\mathrm{E} \sim 100$ GeV ($\mathrm{T} \sim 10^{15}$ K). The strong interactions are described by a separate theory, called *quantum chromodynamics.*[8] The Standard Model includes the electroweak theory and quantum chromodynamics as two independent parts. There are a number of candidate theories, collectively called Grand Unified Theories (GUTs), which attempt to unify the electroweak and strong interactions. Analysis shows that the strong nuclear force gets weaker with increasing energy and becomes comparable to the electroweak force at $E \sim 10^{16}$ GeV. Hence the grand unification must occur at very high energies and temperatures ($E \sim 10^{16}$ GeV, $T \sim 10^{29}$ K). Ultimately, gravity also needs to be unified with the other forces. *String theory* is currently the most promising framework to accomplish this goal (see Chap. 19). It suggests that gravity and the GUT force merge at the Planck[9] energy scale ($E \sim 10^{19}$ GeV, $T \sim 10^{32}$ K).

In the cosmological context, as the universe cools down from the big bang, it goes through a series of symmetry breaking transitions (see Fig. 14.10). Each transition has a Higgs field associated with it; this field is equal to zero prior to the transition and takes a non-zero value once the symmetry is broken. The symmetry breaking transitions occur in rapid succession, so all four interactions become distinct within a small fraction of a second after the big bang.

The electroweak unification and subsequent symmetry breaking are understood theoretically, and well tested experimentally. Unfortunately, the same cannot be said for GUTs. While theorists have proposed many GUTs, it is not so easy to test them because GUT scale energies are inaccessible to particle accelerators. We would need an accelerator that is 3 light years long—almost all the way to Alpha Centauri—to reach GUT scale energies! There is however hope that studies of the early universe might provide an observational window on GUT scale physics. As the Soviet physicist Yakov Zeldovich put it: “The early universe is the poor man’s accelerator”.

[8]Frank Wilczek, David J Gross and H. David Politzer won the 2004 Physics Nobel prize for their work on quantum chromodynamics.

[9]Max Planck pointed out that the only quantity with dimension of energy that can be constructed out of the fundamental constants G, c and $\hbar$ is: $E = \sqrt{\frac{c^5\hbar}{G}} \sim 10^{19}$ GeV. This is the Planck energy.

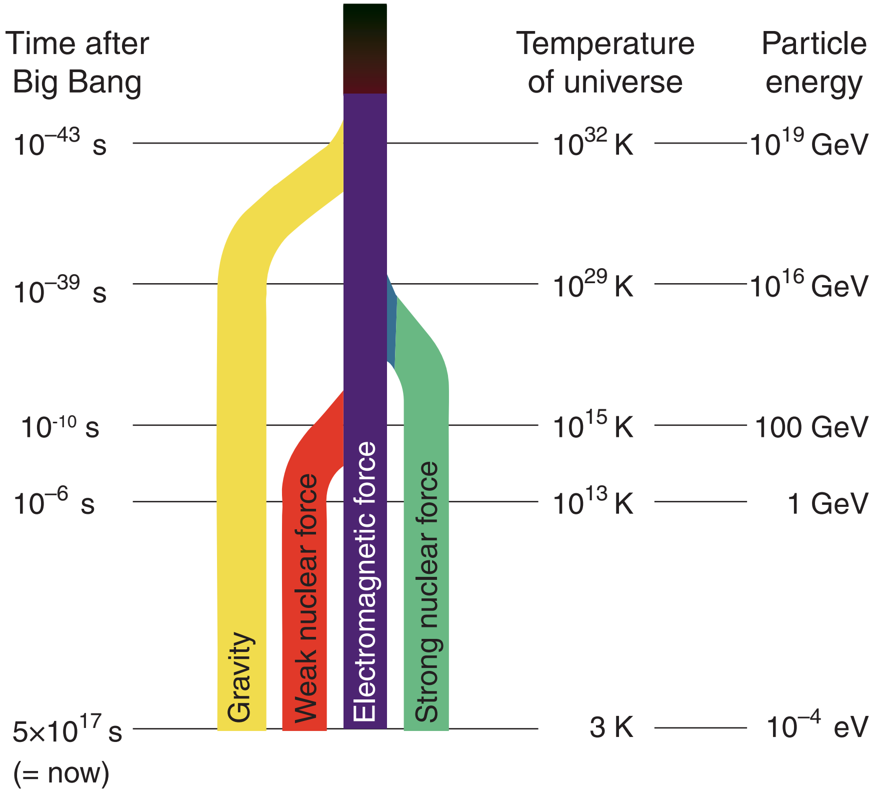

Fig. 14.10 Unification of the four forces. Today the four forces all have a separate identity, but when the universe was much hotter this was not the case. The weak and electromagnetic forces were once the electroweak force. Grand Unified Theories suggest that the electroweak and strong nuclear force were also once united, and split into two forces as the universe underwent symmetry breaking at the GUT energy scale of about 10^{16} GeV. In some models the GUT symmetry is broken in several steps; then there are some additional symmetry breaking transitions between the GUT and electroweak energy scales. String theory seeks to explain how gravity merges with the GUT force at the Planck energy $E \sim 10^{19}$ GeV ($T \sim 10^{32}$ K).

14.6 Vacuum Defects

Symmetry breaking transitions in the early universe can produce a variety of peculiar objects, called vacuum defects, which can still be present in the universe today. Depending on the kind of symmetry breaking, defects can come in three basic types—domain walls, strings, and monopoles. Domain walls are surface-like defects; they are thin sheets of concentrated energy (and mass). Strings are thread-like, with energy distributed along a line. And monopoles are point-like objects, like particles; their energy is concentrated around a single point. Different GUTs predict different kinds of defects. Thus, observation of vacuum defects could provide valuable information about particle physics at very high energies. We shall now discuss the properties of different defects and their possible observational effects. (Note: this section can be skipped without impacting the understanding of subsequent chapters.)

14.6.1 Domain Walls

The simplest model predicting domain walls is the one illustrated in Fig. 14.7.[10] It has two vacuum states, separated by an energy hill. At very high temperatures the Higgs field is equal to zero. Then, as the universe cools below some critical temperature, the symmetry gets broken, and the field has to take one of the two vacuum values, V or −V. The choice between the two vacua is dictated by local random fluctuations, so different parts of the universe end up in different vacua. The universe thus splits into domains having the Higgs field values V and −V, as illustrated in Fig. 14.11.

We can estimate the typical size of the domains, which is denoted by the letter ξ in the figure. If the symmetry breaking occurs at cosmic time t, this size cannot exceed the horizon distance $d_{hor} \sim ct$—simply because no interactions could have occurred over larger distances, so a uniform value of the Higgs field could not be established. For an electroweak-scale symmetry breaking, $t \sim 10^{-10}$ s and the domains must be smaller than 3 cm. For a GUT symmetry breaking, the domains are smaller still, by many orders of magnitude.

Now imagine moving from a domain with the Higgs value V to one with the Higgs value −V. By continuity, at the boundary between the domains, the Higgs field has to go through zero. But we know that the energy density of the Higgs field gets large when the field is set to zero. Hence, the boundaries between positive and negative Higgs domains must carry a large energy. To minimize the energy cost, the regions where the Higgs field is close to

[10]We introduced the two-vacuum model of Fig. 14.7 to illustrate the Standard Model of particle physics, but we emphasize that this is just a schematic illustration. The Higgs field of the Standard Model has three independent components, and the vacuum structure is more complicated. In fact, the Standard Model does not predict any vacuum defects. If any defects are formed, they are likely to come from higher-energy symmetry breakings.

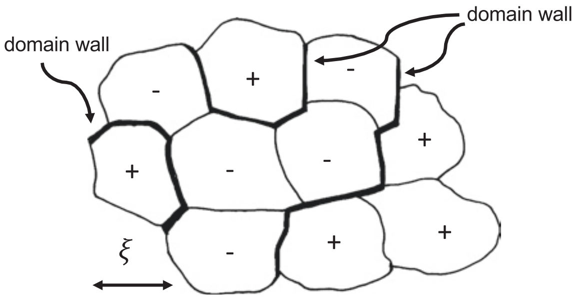

Fig. 14.11 Different physical regions randomly land in one of the two possible vacuum states, separated by domain walls

zero shrink to microscopically thin sheets near the boundaries. These sheets are the domain walls.

You can easily convince yourself that domain walls do not have edges: they can either be closed, completely enclosing domains of positive or negative Higgs field, or they can extend to infinity. The mass per unit wall area depends on the energy scale E_{sb} of symmetry breaking. It is $\sim 10^9$ kg/m^2 for the electroweak scale ($E_{sb} \sim 100$ GeV) and grows proportionally to E_{sb}^3 at higher energies. Thus, for a GUT-scale symmetry breaking the walls carry a mammoth mass of 10^{51} kg/m^2.

Once the symmetry is broken, domains with the same value of the Higgs field begin to merge and grow larger. But they cannot grow faster than the speed of light, and thus the typical domain size will always remain smaller than the horizon. Applied to the present time, this implies that there should be at least one domain wall stretching across the presently observable region. Such a wall would have mass much greater than the combined mass of all matter in this region. The gravity of the wall would then drastically disrupt the observed isotropy of the galaxy distribution and of the cosmic microwave background. Since no major disruptions of isotropy are observed, it follows that particle physics models predicting domain walls should be ruled out. Thus, even though we have not yet observed any vacuum defects, we have already learned something about high-energy particle physics.

14.6.2 Cosmic Strings

Thread-like string defects are predicted in a wide variety of particle physics models. Here is a summary of their basic properties.

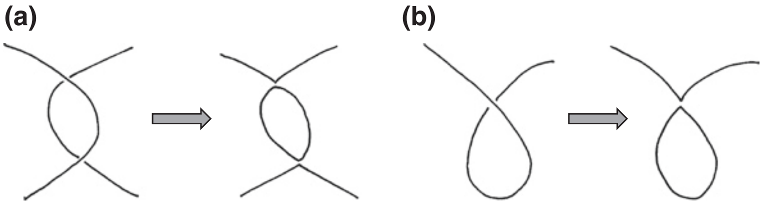

Fig. 14.12 Cosmic strings reconnect as they cross

- Strings do not have ends: they either form closed loops or extend to infinity.
- The thickness of strings is microscopic, while their length can be arbitrarily large. So strings can be well approximated by infinitely thin lines.
- The mass per unit length of a string, usually denoted by μ, is determined by the symmetry breaking energy scale, $\mu \propto E_{sb}^2$. Electroweak-scale strings, if formed, would be very light, $\mu \sim 10^{-7}$ kg/m, while GUT-scale strings would be extremely massive, with $\mu \sim 10^{21}$ kg/m.
- Cosmic strings have a large tension, like in a stretched rubber band. This causes a closed loop of string to oscillate at a speed close to the speed of light.
- When strings intersect, they reconnect, resulting in the formation of closed loops (see Fig. 14.12).

At the time of symmetry breaking, strings form a dense random network, consisting of long, wiggly strings and small closed loops. As for domain walls, the typical distance between the strings in the network cannot exceed the horizon. The subsequent evolution of cosmic strings is rich in physical processes. Tension in wiggly strings causes them to move at relativistic speeds. Moving strings intersect and chop off their wiggles in the form of closed loops. As a result, long strings get straighter with time. Closed loops oscillate and lose their energy by emitting gravitational waves. They gradually shrink and disappear.

Computer simulations have revealed that cosmic string evolution has a scaling property: at any time the string network looks more or less the same, except the overall scale grows proportionally to time. So, if you took a snapshot of the network, say, at $t = 1$ s and magnified it 100 times, it would look very similar to a snapshot taken at $t = 100$ s. In particular, a horizon region at any time contains several long strings and a large number of closed loops, as shown in Fig. 14.13. This applies to the present time as well: if cosmic strings exist, there should be a few long strings stretching across our

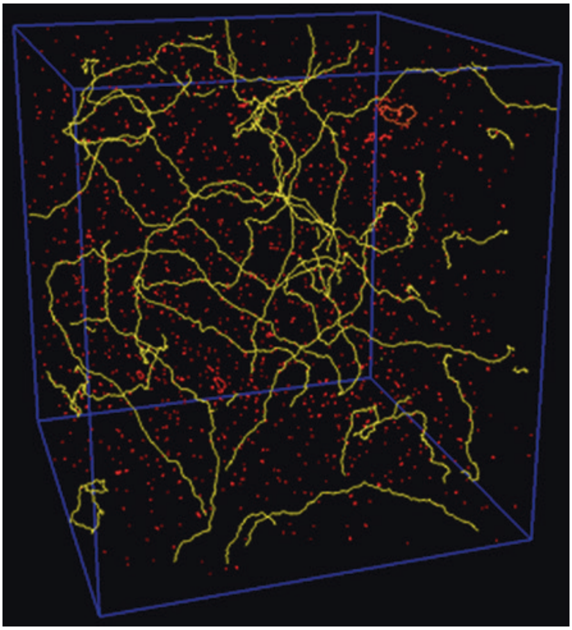

Fig. 14.13 A horizon-size region containing several long strings (shown in *yellow*) and a large number of small closed loops (shown in *red*). This simulation was performed by C. Martins and E.P. Shellard

visible universe. We might then be able to detect these strings through their gravitational effects.

Strings can act as gravitational lenses - light rays propagating to us from a galaxy located behind the string will bend, resulting in two images of the same galaxy. The typical angular separation between the images is proportional to the string mass per unit length μ; for a GUT-scale string it is a few arc seconds. The main difference from gravitational lensing by galaxies is that the two images produced by a string are expected to be nearly identical, while galactic gravitational lenses amplify and distort the images in different ways. Moving strings could also produce a characteristic signature in the CMB: the intensity of cosmic radiation would change discontinuously across the string. None of these effects have yet been observed.

Gravitational waves emitted by oscillating loops add up to a stochastic (or random) gravitational wave background with a very wide range of wavelengths—from microns to light years. The intensity of gravitational waves depends on the mass parameter μ. The fact that no gravitational waves have yet been detected implies $\mu < 10^{19}$ kg/m. This corresponds to $E_{sb} < 10^{15}$ GeV, somewhat below the GUT scale.

14.6.3 Magnetic Monopoles

Monopoles are point-like defects. In many ways they are similar to elementary particles, but they have an unusual feature: each monopole carries a positive (north) or negative (south) magnetic charge. In contrast, all magnets we are familiar with are magnetic dipoles - they always have both a south and a north pole. The mass of a magnetic monopole is set by the symmetry breaking energy scale: $M \sim E_{sb}/c^2$. Thus, for a GUT monopole, $M \sim 10^{16}$ GeV.

As with other vacuum defects, at the time of formation, we expect to have no less than one monopole per horizon region. But unlike other defects, monopoles are predicted in *all* GUTs. This leads to a very serious problem, which we will address in Chap. 15.

14.7 Baryogenesis

At very early times, the primordial fireball was populated by particles and antiparticles in almost equal amounts. But as we noted in Sect. 14.4, there must have been a small imbalance: particles outnumbered antiparticles by about one part in a billion. What was the origin of this tiny asymmetry? Could it have been generated by some physical process from a preceding state containing exactly equal amounts of matter and antimatter?

One obstacle to implementing this idea is baryon number conservation. Protons and neutrons are collectively called baryons, and the baryon number B is defined as the number of baryons minus the number of antibaryons. A universe with equal numbers of baryons and antibaryons would have $B = 0$. To date, all observed particle processes have been found to conserve baryon number. If baryon number conservation is a universal law of nature, then B will always remain zero if it is initially zero. However, according to grand unified theories, the baryon number is only approximately conserved.[11]

[11]One consequence of this is that protons are not absolutely stable and can decay via processes like $p^+ \to e^+\gamma\gamma$. The expected proton lifetime is much greater than the age of the universe, but proton decay can in principle be observed by watching a huge number of protons. However, all attempts to observe it so far have failed and have led only to the upper bound of 10^{34} years on the proton lifetime.

Violations of B-conservation are extremely rare at energies that can be reached in accelerators, but they are expected to be very common in particle collisions at GUT energies. This engenders the possibility of *baryogenesis*—the generation of a nonzero baryon number in the early universe.

B non-conservation is a necessary, but not a sufficient condition for baryogenesis. If the initial state has equal numbers of particles and antiparticles, then the source of asymmetry must be in the laws of physics that govern the subsequent evolution of that state. In other words, the laws of physics should not be completely symmetric between matter and antimatter. In fact, such an asymmetry has already been observed in accelerator experiments. For example, the decay rates of the short-lived B^0 mesons are different for particles and antiparticles.

Yet another condition for baryogenesis is that B-violating reactions should be sufficiently slow, so that thermal equilibrium does not have time to establish. The reason is (roughly) that, in the absence of B-conservation, the density of each kind of particle in equilibrium is determined only by their mass. Since particles and antiparticles have the same mass, it follows that they have equal densities in equilibrium.

To see how baryogenesis may occur in the absence of equilibrium, consider the following scenario. Suppose some hypothetical X-particles and their antiparticles have asymmetric B-violating decays, so that the decay products of a particle and an antiparticle have a positive net baryon number. In the early fireball, the particle density is very high, so X-particles frequently collide and annihilate, and particle-antiparticle pairs are frequently produced in collisions of photons (and other particles), so equilibrium is established. When the temperature drops below the X-particle mass, the photon energies are no longer sufficient to produce X-pairs. Also, the particle density has now significantly decreased, so the collisions between X-particles are rare and their annihilation is inefficient. The surviving X-particles are now out of equilibrium. They eventually decay and generate a nonzero baryon number.

The three conditions for baryogenesis—baryon non-conservation, particle-antiparticle asymmetry in the laws of physics, and non-equilibrium—were first formulated in 1967 by Andrei Sakharov—the Russian physicist who is mostly known for his role in the development of the Soviet hydrogen bomb and later as a prominent dissident opposing the Soviet regime. Since then, cosmologists have suggested a number of models where these conditions are satisfied, so the observed baryon number can be generated. We don't know which, if any, of these models is correct, but most cosmologists accept the general idea—that the matter excess over antimatter was generated by B-violating processes in the early universe.

Summary

To understand the early universe we need to understand the physics of the microworld. Around one second after the big bang, the universe was a hot fireball of electrons, protons, neutrons, photons and neutrinos. As we go farther back in time, the fireball gets hotter and denser and gets populated with other types of particles. We now have a very successful theory, called the Standard Model, which accurately describes all known particles and their interactions. There are, however, strong indications that the Standard Model is not the whole story. In particular, it does not account for some properties of neutrinos and for the existence of new (unknown) particles that constitute the dark matter.

Extensions of the Standard Model are inspired by the idea that the four fundamental forces—gravity, electromagnetism, and the strong and weak nuclear forces—are in fact different manifestations of a single, unified force. At very high energies distinctions between the different forces disappear; this is what happens at extremely high temperatures in the early universe. As the universe cools down, the symmetry between the forces is broken in several steps.

Even though the cosmic symmetry breaking transitions occurred when the universe was only a fraction of a second old, they might have left some remnants, which could be present in the universe today. These include point-like magnetic monopoles, line-like strings, and sheet-like domain walls.

Grand Unified Theories may be able to explain how an excess of matter over antimatter could have been created. GUTs predict that baryon number is not conserved, allowing for a nonzero baryon number to be generated in the early universe.

Questions

1. Why are particle accelerators so useful to cosmologists?
2. What is a positron? How are its mass and charge related to those of an electron?
3. Name two key physical properties that must be conserved when particles are produced in collisions.
4. Can two protons collide and produce two photons only? Why/Why not?

5. Can two photons of energy 0.1 MeV collide and produce an electron-positron pair?
6. List the four known fundamental forces of nature. Also indicate what role each of these forces has in nature and which bosons are responsible for mediating each force.
7. Since like charges repel, why do nuclei with many protons stay together instead of exploding apart?
8. What mass would all Standard Model particles have if the Higgs field were zero?
9. Briefly describe what happened immediately before and after the following two epochs in the very early universe:
   (a) The electroweak phase transition ($t \sim 10^{-10}$ s, $T \sim 10^{15}$ K)
   (b) Quark confinement ($t \sim 10^{-6}$ s, $T \sim 10^{13}$ K)
10. During the quark confinement era, protons and neutrons are formed for the first time, and most of them undergo annihilation with their anti-particles shortly thereafter. What happens to the surviving protons and neutrons? When did the protons and neutrons in your body originate?
11. Prior to the electron-positron annihilation era, there had to have been an excess of electrons over positrons. Roughly how big was this excess?
12. What is the difference between a scalar field and a vector field? Can you give an example of each?
13. In what sense is a snowflake less symmetric than a spherical drop of water?
14. Name two key features of our universe that the Standard Model does not include.
15. Which two seemingly disparate phenomena did Maxwell unify in his theory? What was his theory called?
16. Which two phenomena does the electroweak theory unify?
17. Do Grand Unified Theories include all of the forces of nature? Explain.
18. Are Grand Unified Theory (GUT) scale energies accessible to particle accelerators? If not, how can we hope to study GUT scale phenomena?
19. Some particle physics models predict the existence of defects called domain walls. What is a domain wall?
20. Why should particle physics models that predict domain walls be ruled out?
21. Do cosmic strings have ends?
22. What property of cosmic strings causes them to move with a velocity approaching that of light?
23. In string simulations, do strings become more or less wiggly with time?

24. Name one method physicists use to look for cosmic strings.
25. What is a magnetic monopole?
26. Is the statement “Diamonds are forever” consistent with grand unified theories?”