

16.2: Particle Soup

Learning Objectives

- You will know the fundamental particles.
- You will know the fundamental forces.
- You will be able to calculate the ambient temperature corresponding to the mass-energy of particle reactions.
- You will know that at different temperatures, the Universe undergoes various transitions: electroweak transition, quark confinement, proton-antiproton annihilation, neutrino decoupling, and electron-positron annihilation.
- You will know that the electromagnetic, weak, and strong forces were once unified.

What Do You Think: particles



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Big Bang nucleosynthesis is a triumph of modern physics. Its ability to predict what conditions were like in the early Universe is remarkable. Still, it can only take us back to a time when the Universe was a bit under a second old, and it describes the overall evolution of the Universe for several hundred seconds thereafter. What occurred at earlier times, when the Universe was much less than a second old, BBN cannot tell us. It might seem ridiculous to ask what the Universe was like at such early times, but just as we can use our understanding of physics to paint a picture of the BBN era, we can also use it to try to predict what conditions would have been like at earlier times. However, when we go further back in time the conditions become more extreme and the physics becomes less certain.

Using our knowledge of physics as our guide, the next step takes us back to times when the Universe was just a tiny fraction of a second old and things were packed more than a billion times closer together than during the BBN era. The Universe was a sea of subatomic particles because temperatures were much too high for atomic nuclei to be stable.

16.2.1: Elementary Particles

To get a feel for how scientists classify particles based on their properties and interactions, you will classify some fictional particles in the following activity. You will use criteria of your own choosing.

Particle Classification

The purpose of this activity is to help you understand how scientists classify the fundamental particles.

Listed in a table, you will see 13 hypothetical particles and some of their properties. These properties include mass, electric charge, and two quantum properties called “spin” and “color charge.” For both mass and color charge, the possible values are either “yes” or “no.” Electric charge can be either positive or negative and have a variety of different values. Spin is either an integer or half-integer number.

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In the last activity you classified a number of hypothetical particles. The actual fundamental particles in our Universe are shown in Figure 16.12, arranged into a few categories. Each particle also has a corresponding anti-particle, which has the same properties as the particle except its charge is reversed.

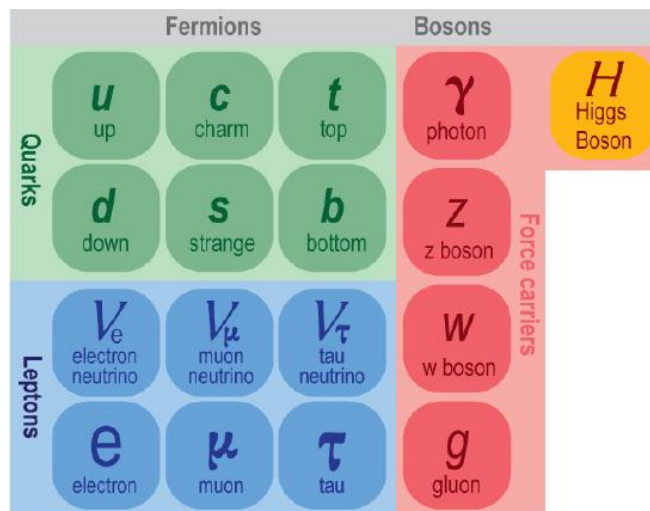


Figure 16.12: All matter is composed of combinations of quarks and leptons. Each of these particles has a corresponding antiparticle with opposite charge. In addition, there are the force-carrier particles by which the matter particles interact with one another. These are shown in the right-hand column. The recently discovered Higgs particle is also a fundamental particle. Credit: NASA/SSU/Aurore Simonnet

All matter is composed of combinations of the fundamental particles shown in Figure 16.12. All of the atoms from which we are made are composed of combinations of protons and neutrons (which together are called nucleons) and electrons. Protons and neutrons are each composed of three quarks. The sub-structure of an atom is shown schematically in Figure 16.13. You can see that protons and neutrons each contain one down and one up quark. It is the third quark that differentiates the two particles.

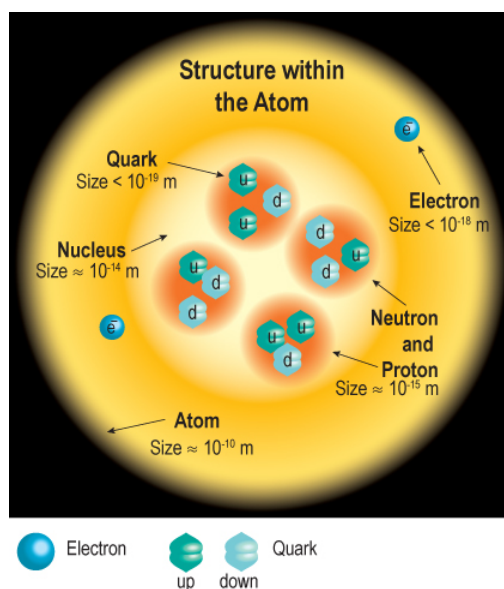


Figure 16.13: The nuclei of atoms are composed of protons and neutrons, which are in turn composed of quarks. Electrons orbit the nucleus in a large cloud. Credit: NASA/SSU/Aurore Simonnet

There are four additional quarks, called charm, strange, top, and bottom, making six quarks total. The names are whimsical and are not intended to convey any of the properties of the particles themselves, though charm, strange, top, and bottom do have slightly different properties from up and down, in addition to having higher masses. None of the heavier quarks are stable. In the current conditions in the Universe they all decay, often through complex reaction chains, into lighter particles that are stable. There are hundreds of (mostly short-lived) particles that do not combine to form chemical elements (atoms). These are built from various combinations of two or three quarks.

Particles made of three quarks are called baryons, and particles made of two quarks are called mesons. The general name for particles made of quarks is hadron. Quarks have fractional electric charge. They combine to make hadrons of integer charge. For example, an up quark has a charge of $+2/3$ and a down quark has a charge of $-1/3$, so a proton, which is made of two up quarks and one down quark, has a charge of $2/3 + 2/3 - 1/3 = +1$. A neutron, which is two down quarks and one up quark, has a net charge of $2/3 - 1/3 - 1/3 = 0$.

In addition to the quarks, there are lighter particles, similar to the electron, but with higher mass. These are the muon and the tau particle. You can think of these as heavier versions of the electron. And like the electron, each has its own version of the neutrino. The light particles are collectively called leptons; there are six leptons total, just like the quarks.

From these particles, together with the force-carrier particles and the Higgs particle, nearly all of the physical properties observed (so far) in the Universe can be explained.

16.2.2: Four Fundamental Interactions

The four fundamental interactions (or forces) are: the **electromagnetic interaction**, which keeps electrons bound to atomic nuclei and thereby determines the structure of atoms; the **strong nuclear interaction**, which holds the nucleus and the particles in it together; the **weak nuclear interaction**, which is important in radioactive decay; and **gravity**, which dominates on large scales.

Each of these interactions is mediated, or carried by, associated particles called field bosons. An analogy for a carrier particle would be a ball that two people are passing back and forth; as long as the two people are passing the ball, they are interacting. Fundamental properties of the interactions depend on the properties of the carrier particles involved. To take one example, the particle that carries the electromagnetic interaction is the photon, a particle of light. The electromagnetic force has infinite range because the photon is massless and has no charge. For the strong nuclear interaction, an exchange of gluons, which are also massless, holds quarks together to form larger particles. Because gluons interact strongly with each other, the force acts over only extremely short ranges, comparable to the size of an atomic nucleus. The weak interaction is mediated by W and Z bosons, which are heavy and short-lived. This limits weak interactions to an even shorter range.

Though gravity has so far defied this concept of carrier particles, in a quantum theory of gravity, the gravitational force would be mediated by massless gravitons. This would imbue the gravitational interaction with infinite range. The quantum view is very

different from the geometrical framework of general relativity. Thus far, the two systems have yet to be mathematically unified, and research into a theory of quantum gravity is ongoing and robust.

We have described electromagnetic and gravitational forces extensively in other chapters. They are both important for many cosmological phenomena. The weak and strong nuclear forces are not obviously at work in the present day Universe, though of course both are critical. But because neither operates on macroscopic scales, they were not even known to exist until well into the 20th century, when scientists began to probe the structure of atomic nuclei. Nonetheless, they become especially important in the early Universe, when conditions everywhere were similar to, or even more extreme than, the conditions in nuclear reactors and particle accelerators.

For example, the weak interaction can convert a neutron to a proton and vice versa (Figure 16.14). It is fundamentally different from the electromagnetic interaction—it follows a different set of rules and involves a different set of particles. For example, weak interactions do not act only on charged particles. In the conversion of a neutron to a proton, two charged particles and two neutral particles are involved. The interaction converts one of the down quarks in the neutron into an up quark, an electron, and an anti-neutrino. The electron and anti-neutrino fly away. The up quark remains in the nucleon, which is now a proton (uud) instead of a neutron (ddu). At a more fundamental level, there is an exchange of W bosons with one of the down quarks in the neutron that mediates the conversion.

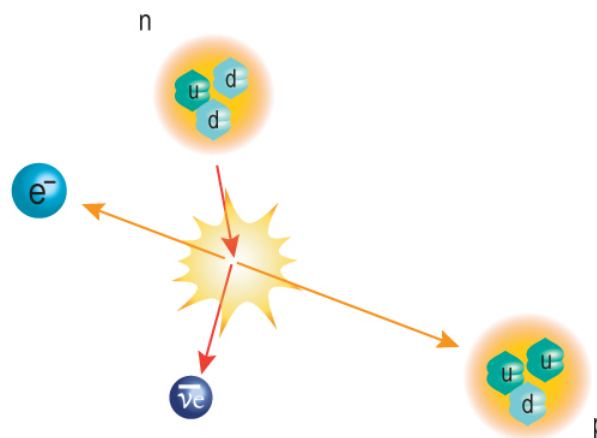


Figure 16.14: When a neutron decays, one of the down quarks in the neutron turns into an up quark, and thus the neutron (udd) turns into a proton (uud). In this weak interaction an electron and anti-neutrino are also produced. The electron is necessary for total electric charge to be conserved, which all known interactions do. Credit: NASA/SSU/Aurore Simonnet

The weak interaction is called weak for historical reasons, but that is a bit of a misnomer. The interaction is rare in a sense, but that is not because it is weak; it is because the interaction has a short range. Whereas electromagnetic and gravitational interactions have an infinite range that falls off like $1/r^2$, the weak interaction seems to have a finite range. Weak interactions occur only if particles are about 10^{-16} m from each other. This is about a million times smaller than the diameter of an atom—or about 10 times smaller than the diameter of a proton. Particles don't often approach one another so closely. That is why the weak interaction seems weak.

Like the weak force, the strong force also has a finite range, about 10^{-14} - 10^{-15} m, the size of atomic nuclei. At these scales, the strong force is about 100 times stronger than the electromagnetic force. This difference in strength is important for overcoming the repulsive force between protons in nuclei, which are positively charged. The strong force binds protons and neutrons to each other inside atomic nuclei. It also binds the quarks within nucleons together.

Quarks have a property, known as color charge, that determines how they combine to form hadrons. Color charge has nothing to do with colors of the electromagnetic spectrum. It was given that name because of the way the quarks must combine. There are three types of color charge: red, green, and blue, along with three complimentary colors for the anti-quarks: anti-red, anti-green, and anti-blue. To make a particle, the color combination must be color-neutral. For example, to make a baryon, which consists of three quarks, one red, one green, and one blue quark must be used. Just as a combination of red, green, and blue light makes white light on a computer screen, one red up quark, one green up quark, and one blue down quark can make a proton. To make a meson, which consists of two quarks, a red and anti-red, or green and anti-green, or blue and anti-blue combination must be used.

If you would like to learn more about particle physics, visit the [Particle Adventure](#) website.

16.2.3: Matter-energy Conversion and the Temperature of the Universe

In the conditions of the very early Universe, matter and photons exchanged energy with each other and could be described by a single temperature, similar to the interiors of stars today. However, conditions throughout the Universe in the first fraction of a second were far more extreme than exist in any star. Temperatures and densities were both much, much higher than any star can produce.

We know that energy and mass can be converted back and forth into each other ($E = mc^2$). Subatomic particles can be turned into one another (following the rules of the force interactions) as long as there is enough energy for the reaction to run. At high enough temperatures, this happens spontaneously. The energy can come from the environment if the temperature is high enough. In that case, collisions between particles are able to furnish the required energy.

For instance, when temperatures are high enough, a photon can spontaneously convert to an electron—positron pair upon interacting with another particle (Figure 16.15). The additional particle is necessary to conserve momentum; a photon converting on its own is not able to simultaneously conserve both energy and momentum. An electron and a positron can also combine to create two photons in the opposite process, which is known as annihilation. In general it is necessary to solve equations for both conservation of momentum and conservation of energy simultaneously in order to describe these interactions. However, our purpose here is to gain insight into how energetic photons must be in order for the energy conversion process to be viable.



Figure 16.15: At high enough energies it is possible for a photon to spontaneously convert its energy into particles. The process must involve another particle, which must carry away some of the momentum of the photon. The opposite process, annihilation, occurs when a positron and electron combine to form a pair of photons. Each photon carries the energy of the rest mass of one of the original particles, thus conserving energy. However, two photons must be created in order to conserve the momentum of the original particles. Credit: NASA/SSU/Aurore Simonnet

As another example, in the early Universe, protons were able to turn into neutrons (Figure 16.16) because the environment supplied an ambient amount of energy corresponding to the difference in their masses.

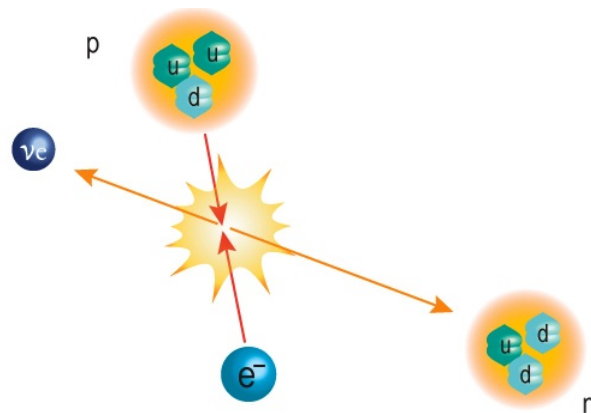


Figure 16.16: Protons and neutrons are made of different combinations of quarks. If the collision between a proton and electron is energetic enough, some of the energy of the collision can convert an up quark in the proton into a down quark, thus turning the proton into a neutron. The interaction also produces an electron anti-neutrino and occurs because of the weak force. Credit: NASA/SSU/Aurore Simonnet

In order to determine how much energy the environment can supply, we must relate the typical kinetic energy of particles (E) in a gas to the temperature of the gas (T). From thermal physics, we know that the relationship between the two is as follows.

$$E \sim kT$$

The k here is the Boltzmann constant, 1.381×10^{-23} J/K. This means that when the temperature of a gas is higher, it has more energy because the particles in it are moving faster. This fundamental relation tells us that temperature is a way of describing the typical energy of the particles in a system in equilibrium.

Combining this expression between energy and temperature with the relationship between energy and mass, we can find the ambient temperature needed in the environment for a given particle reaction to occur:

$$T \sim \frac{\Delta mc^2}{k}$$

In the following activity, we will explore the relationships between mass, energy, and ambient temperature.

Particle Reactions and the Temperature of the Universe

Worked Examples: Electron-Positron Creation and Annihilation

If we imagine that a photon converts its energy into an electron and a positron, then we can ask what the energy of the photon must be and at what temperature this conversion would be likely to occur. We'll find the energy first.

a. The rest mass of a positron is the same as that of an electron: 9.1×10^{-31} kg. What is the rest energy of these two particles?

- Given: $m = 9.1 \times 10^{-31}$ kg
- Find: E
- Concepts: $E = mc^2$
- The rest energy of a positron is the same as that of an electron since both have the same mass. We need a photon with twice this amount of energy in order to create both an electron and a positron.
- Solution: the total energy of the photon is: $E = 2mc^2 = (2)(9.1 \times 10^{-31} \text{ kg})(3 \times 10^8 \text{ m/s})^2 = 1.637 \times 10^{-13} \text{ J}$

This is a tiny amount of energy by everyday standards. However, we can compare it to energy scales more relevant to atomic and subatomic systems. We have already learned that the energy of visible light is around 10^{-19} J, an even smaller number. We generally speak of the energy of light in units called electron-volts ($1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$), and a visible light photon typically has energy of around one or two eV. This is a better way to describe the energies we are talking about because we do not have to worry about inconvenient factors like 10^{-19} .

b. Find the energy of the photon needed to create an electron-positron pair in terms of electron-volts.

$$E = (1.637 \times 10^{-13} \text{ J}) \times (1 \text{ eV} / 1.602 \times 10^{-19} \text{ J}) = 1.02 \times 10^6 \text{ eV}$$

To put this into perspective, this photon is about a million times more energetic than visible light, and also about a million times more energetic than the bonds holding the outer shell electrons in most atoms. We would classify it as a gamma-ray photon. Though not particularly energetic by gamma-ray standards, it would still be about a thousand times more energetic than the x-rays one encounters at the dentist or doctor's office. Note that when we perform calculations we must always use the same set of units; in this case we have chosen SI. We only use electron-volts for convenience in understanding energies that would be extremely small in terms of joules, which are the SI unit of energy.

c. Now that we know roughly how energetic a photon must be to spontaneously create an electron-positron pair, we can ask how hot a gas containing such photons must be. What is the temperature of the gas?

- Given: $E = 1.637 \times 10^{-13} \text{ J}$, energy of the photon
- Find: T , temperature of the gas
- Concepts: We know that the typical kinetic energy of the particles in a gas is given by $E \sim kT$, where k is the Boltzmann constant, $k = 1.38 \times 10^{-23}$ J/K, and where the temperature T must be measured in kelvin. To find the temperature give the energy, we will use $T \sim E/k$.
- Solution: $T \sim E/k = (1.637 \times 10^{-13} \text{ J}) / (1.38 \times 10^{-23} \text{ J/K}) = 1.2 \times 10^{10} \text{ K}$

This is about 10 billion kelvin, an incredibly high temperature. You might recall from our discussion in the last section that it is the same temperature scale that existed during the BBN era. That means that while all of the neutrons in the Universe were being consumed to make helium, the photon background—at that time gamma-rays, not microwaves as it is today—was busily converting between e^+e^- pairs and back again. These were the conditions throughout the Universe when it was a second or so old.

When we compute the temperature as in the previous example we are merely getting an idea of how hot a gas must be for pair-conversion to occur. In fact, gases contain particles with a range of energies, and the temperature describes only the typical (the average) energy of a particle in the gas. Some particles (photons included) will have higher than the typical energy, so we expect that pair production will occur in somewhat cooler gases than we have found with our estimate. For an example exploring the inter-conversion between protons and neutrons, see [Math Exploration 16.1](#).

Math Exploration 16.1

Questions: Proton—Antiproton Creation and Annihilation

Looking to still earlier times, we expect the temperature to be ever higher. At some point in its history, the temperature was high enough for photons to create proton—antiproton pairs (Figure A.16.2). Now you will estimate the temperature at which this process can occur.



Figure A.16.2: At high temperatures photons spontaneously produce a proton and an antiproton, as shown at left. The particles will quickly combine with other protons or antiprotons and annihilate, as shown at right, creating two photons. These two processes keep each other in balance until the temperature drops to the point that photons are no longer energetic enough to produce the proton—antiproton pairs. Credit: NASA/SSU/Aurore Simonnet

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After the temperature dropped below the critical point you just computed, there was not enough ambient energy in the environment to run the reaction both ways. Protons and antiprotons annihilated and turned into photons, but the reverse no longer happened.

In the previous activity, you learned how to calculate the ambient temperature of the Universe corresponding to the energy required for several particle reactions. These processes have important consequences for how the early Universe changes over time. We can calculate which particles can exist and in what form at different times based on the temperature of the Universe at those times.

16.2.4: Transitions in the Early Universe

In the last section, we saw how the temperature of the Universe corresponds to energies of possible particle reactions and therefore dictates how the Universe takes on different characteristics over time. Now we will look at some of the key events and the corresponding conditions in more detail. As we will see, the temperature also affects the fundamental interactions. We will consider these events by running time forward from around 10^{-12} seconds to about 1 second, from higher temperatures to lower temperatures. The events are summarized graphically in the timeline of Figure 16.17.

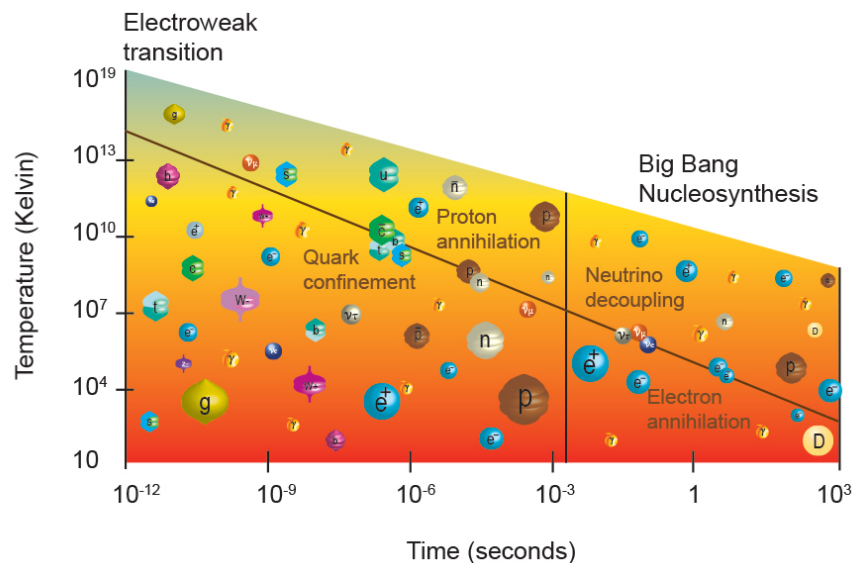


Figure 16.17: Conditions in the early Universe depend on its temperature. When the ambient temperature is greater than or equal to the energy of a particle reaction, it can run both ways, but when the temperature drops, the reaction typically only runs one direction. This dictates which particle structures are present at what times. When the temperature is high, structures are simpler; more complex structures are built up as the Universe cools. Credit: NASA/SSU/Aurore Simonnet

16.2.4.1: Quark-gluon plasma, $t < 10^{-12}$ s, $T > 10^{15}$ K

At early times, conditions were even more extreme than during BBN. There were no complex structures, atoms, or even nucleons (protons and neutrons), because the collision energies were so high that atoms were unstable: they were more likely to be destroyed by collisions than to be created by them. Instead, matter consisted of a zoo of sub-atomic particles constantly converting between matter and energy. Temperatures were high enough to generate every kind of known subatomic particle, and they all existed together in approximately equal numbers in a bizarre dense "soup" called a **quark-gluon plasma**. Free quarks and gluons, as well as photons, electrons, neutrinos, and exotic particles like W and Z bosons and Higgs bosons, the heavy quarks and leptons, and perhaps other particles as well, were all spontaneously formed and annihilated with their antiparticles.

This state of matter is usually referred to as the quark-gluon plasma, not because it contains only quarks and gluons, but because those are the primary components of matter at such extreme temperatures and densities. Scientists are currently attempting to recreate the quark-gluon plasma in laboratories, where giant particle accelerators smash large atomic nuclei—not just protons and antiprotons - into each other at near the speed of light. In fact, it is from these sorts of collisions between large hadrons that machines like the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) take their names. Hadrons are particles composed of quarks, so they include baryons and also atomic nuclei, which are composed of baryons.

16.2.4.2: [*Electroweak transition, \$t = 10^{-12}\$ s, \$T = 10^{15}\$ K*](#)

At early times, when the Universe was dense and hot, with a lot of ambient energy available in the environment, the distinction between the electromagnetic and weak interactions was not apparent. They were unified into the electroweak interaction. The discovery of this unification was a drawn-out process, and physicists have only come to fully understand it over the past several decades.

The unification is similar in spirit, if not in detail, to that achieved by James Clerk Maxwell in the 19th century when he unified the until-then distinct electric and magnetic forces into the electromagnetic force. Maxwell was able to write all electromagnetic interactions in terms of a single mathematical framework (theory), and since that time physicists have wondered if it might be possible to develop a single theory that describes all four of the known forces in a similar way. In the 1970s, physicists Sheldon Glashow (b. 1932), Abdus Salam (1926–1996), and Steven Weinberg (b. 1933) developed the mathematical framework for the unification of the electromagnetic and weak interactions.

The electroweak unification is only apparent at very high temperatures, when typical particle energies are above 100 GeV (10^{11} eV). These are energies that are easily attained by particle accelerators of the past several decades, and so the physics of the electroweak interaction has been well—studied in laboratories. To find a time when the entire Universe could be described by such energies, when the temperature was more than 10^{15} K, we have to go back to the first 10^{-12} seconds of its existence.

16.2.4.3: [*Quark confinement, \$t = 10^{-6}\$ s, \$T = 10^{13}\$ K*](#)

By about 10^{-6} seconds, quarks and antiquarks had cooled and slowed sufficiently that they could bind together in groups of three to produce protons and neutrons and their antiparticles. There was not enough energy to break the new compound particles apart, so this is when almost all of the protons and neutrons in the Universe were made, including those that make up your mass. Protons have stayed intact for 13.8 billion years, and they will stay intact for trillions of years more. Quark confinement is the first time the Universe creates composite (non-elementary) particles, and it is the first step toward the great complexity we see now in the Universe.

16.2.4.4: [*Baryon annihilation, \$t = 10^{-4}\$ s, \$T = 10^{12}\$ K*](#)

When the Universe was about 10^{-4} seconds old and the temperature dropped below about 10^{12} K, it was no longer possible to spontaneously produce protons and antiprotons from light. So soon after all the protons and neutrons were made they collided with their antimatter equivalents, composed of anti-quarks, producing huge numbers of photons. In every cubic centimeter of the Universe 100 million tons of matter and 100 million tons of antimatter converted into pure energy. To put this annihilation event into perspective, just the annihilation of the matter in your hand would produce the same amount of energy as a 10 megaton hydrogen bomb.

The great surprise—and a puzzle—is that a small number of protons and neutrons survived this carnage. In producing proton–antiproton pairs, standard particle theory plays no favorites. The photons should create just as many antiprotons as protons, and when the two annihilate they should convert completely back to photons. There should be no protons (or neutrons) left. However, there must have been an imbalance, because the Universe is overwhelmingly dominated by matter (and does not contain much antimatter). If there was a lot of local antimatter, we would see many energetic annihilation events all around us. If there were distinct matter and antimatter regions in the Universe, we would see annihilation events at the boundaries of these regions.

Therefore, there must have been a time early in the Universe when certain reactions produced slightly more “matter” than “antimatter” particles. It is from this excess of matter that all current matter is made. Out of every few billion particles, a single proton emerged that did not find an antimatter proton with which to annihilate. That number is easy to determine because annihilations produce photons, so the baryon-to-photon ratio tells us the ratio of survivors to annihilations. Without this tiny matter–antimatter asymmetry, the Universe would be empty of matter. This asymmetry resulted in a Universe today that is not just photons, but contains enough surviving protons and neutrons to make stars, galaxies, and us.

16.2.4.5: [*Neutrino decoupling, \$t = 1\$ s, \$T = 10^{10}\$ K*](#)

Neutrinos are elusive particles. They interact with protons, neutrons, electrons, and positrons via the weak force, as described in Section 14.2.2. Because they only feel gravity and the weak nuclear force, neutrinos can easily travel through immense thicknesses of lead without interacting with anything. Before the Universe was about 1 s old though, the matter density of the Universe was high enough for them to interact often. After 1 second the Universe was no longer dense enough for neutrinos to react, and they decoupled in an event similar to the one that occurred for photons about 380,000 years later - when they formed what is now the CMB. Since that time, neutrinos have been free to fly across the Universe unhindered. Some of them are passing through you now.

If we can ever develop sensitive neutrino detectors, we will be able to obtain a picture of the Universe when it was 1 second old, just as the CMB reveals an image of the Universe at an age of 380,000 years.

16.2.4.6: [Electron–positron annihilation, \$t = 10\text{ s}\$, \$T = 4 \times 10^9\text{ K}\$](#)

By an age of 10 seconds, the Universe had cooled to a temperature of $4 \times 10^9\text{ K}$. At higher temperatures and earlier times, the Universe had enough ambient energy to create electron–positron pairs. Photon collisions produced electron–positron pairs, and when electrons and positrons collided, they produced photons. After this time there was no longer enough energy in the photons to produce electron–positron pairs and annihilation became a one-way process. Electrons and positrons annihilated, leaving huge numbers of photons and slightly more matter (electrons) than antimatter (positrons). The energy released at this time was equivalent to a 5000-megaton nuclear bomb in every cubic centimeter of the Universe.

The photons produced by matter–antimatter annihilations scattered off of the remaining particles (mainly free electrons) until about 380,000 years later when the Universe became transparent and the CMB was formed.

Electrons and neutrinos are key ingredients in the reaction that turns protons into neutrons via the weak force, so both electron–positron annihilation and the neutrino decoupling that happens right before it have important implications for Big Bang nucleosynthesis.

Particle Creation Timeline

In this activity you will combine elementary particles to create more complex ones, and you will determine where each step fits into a timeline of the early Universe.

[Play Activity](#)

A. Combining quarks

First you will see a plasma of up and down quarks of various color charges. Combine the quarks to create nucleons (protons and neutrons).

- To combine particles, click on them.
- A proton is made from 2 up quarks and 1 down quark.
- A neutron is made from 1 up quark and 2 down quarks.
- Particles made of quarks (hadrons) must be color-charge neutral, that is, composed of one red, one green, and one blue quark.

B. Combining nucleons

Combine the protons and neutrons to make all of the particles in the list at the bottom of the screen. The particles will light up when you have created the first one—you only need to make one of each particle type in order to proceed to the second part of the activity.

C. Timeline

Click and drag the particles to place them on the appropriate location on the timeline.

16.2.5: The Gut Time

Before the electroweak era, our understanding of the physics of the early Universe becomes much less certain. Thus, our picture of the Universe at those earlier times becomes correspondingly fuzzy. For instance, we think that, just as electromagnetism and the weak interaction combined at temperatures of 10^{15} K and energies around 100 GeV , it should be possible for the electroweak interaction to combine with the strong interaction at an even higher energy and temperature. This [Grand Unified Theory \(GUT\)](#) of the strong, weak and electromagnetic interactions is thought to become applicable at extremely high energies, although, at the present time, we do not know the exact value of the energy at which this “grand unification” occurs.

Present calculations indicate that the GUT threshold will be found somewhere around 10^{15} GeV . This is far beyond the capabilities of current particle accelerators and exceeds the energies of those likely to be built in the foreseeable future. The GUT threshold is an enormous energy that is equivalent to about 100 kilojoules *per particle* in the plasma. To put this energy into perspective, recall that the energy of a visible light photon is about 1 eV. To use a different comparison, a 90-mph fastball has about 120 joules of

kinetic energy, so at the GUT energy scale, the *typical* particle energy is one thousand times higher than that of a fastball. The next activity asks you to convert this energy to its corresponding temperature scale.

The Gut Scale

At the GUT era of the Universe, the energies of particles are calculated to be at least 10^{15} GeV.

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In this last activity, you determined the approximate temperature at which the strong, weak, and electromagnetic forces would all be unified into a single force. The transition to this GUT era would have occurred around a time of 10^{-35} seconds. GUT theories cannot now be experimentally tested because we cannot currently build accelerators that reproduce such high energies. However, the strong, weak, and electromagnetic forces can all be consistently explained within the framework of quantum mechanics.

So far, and within the framework of the Big Bang theory, we have probed the history of the Universe back to the first fraction of a second as described by well-tested laws of physics, including quantum mechanics, particle physics, nuclear physics, thermodynamics, and general relativity. But could there be additional phenomena, ones that are not explained by the basic Big Bang theory? How early in the history of the Universe can we probe? That is what we will examine next.

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