

In this section: the earliest stage that is well-understood is the quark soup: when the Universe was still too hot and dense to allow protons and neutrons to exist individually.

▷ This is nothing more than the kinetic temperature: express the energy E of 1 TeV in ordinary units (joules) and set it equal to $3kT/2$ to find T . You will get about 10^{16} K.

The expansion of the quark soup and its radiation

What was the Universe like at 10^{-10} s? If the Universe is highly homogeneous today, it must have been more so at these early times, since all the structure we see today (galaxies, and so on) developed at a later time as the Universe cooled down. We will describe the way structure developed later in this chapter. But little of it was present when the Universe was a hot ball of gas with a typical particle energy of 1 TeV and a corresponding temperature of 10^{16} K.

Ordinary matter as we know it could not exist at these temperatures. If there were any ordinary protons around, then their random collisions would break them up into their constituents, which physicists call quarks. Quarks are the oddest particles in physics: in groups of three they make protons or neutrons, and in groups of two they make π -mesons and other lighter particles. Yet one never sees them alone: single quarks cannot be peeled off from particles in accelerators. In the early Universe, the particles were packed so closely together that quarks were never alone. Instead, they blended together in a sea that physicists call the **quark soup**.

Besides quarks, there were many other particles in the early Universe. Whatever particles now constitute the dark matter were already there, but their density irregularities, which would be important for galaxy formation later on, were not significant at this time. The dark matter particles were neutral and had stopped interacting with the quarks or the photons by this time. They were already just a provider of a gravitational background.

And there were photons. With energies typical of the thermal energy, they had enough energy to form new quarks in reactions where two photons collide and two quarks emerge. By mechanisms like this and the reverse, the numbers of quarks and photons were maintained in a steady balance.

When particles like quarks or protons are produced by photons that collide with one another, they emerge with equal numbers of particles and anti-particles. The anti-particle of any particle has the opposite sign of the charge. So if electrons are produced, one is a normal electron and the other is a positron, or positively charged electron. If a proton is produced, an **anti-proton** (with a negative charge) is also produced. The anti-particle of a photon is just another photon. So in this way, no net charge is produced: the two photons initially have zero charge, and the two particles that emerge have zero total charge.

When an anti-particle and a particle of the same type collide, the result is often to produce a pair of photons, which is the time-reverse of the reaction described in the previous paragraph. Thus, a proton and anti-proton will annihilate each other to produce two photons. Similarly, a positron and an electron annihilate to two photons. Physicists refer to positrons, anti-protons, anti-neutrons, anti-quarks, and so on collectively as **anti-matter**.

The laws of physics prefer matter over anti-matter

In this section: if the laws of physics were perfectly symmetrical between matter and anti-matter, all matter would have been annihilated and we would not be here. We owe our existence to a small preference in the laws of physics for matter over anti-matter.

As the Universe expanded, the mean distance between quarks grew until they began to get too isolated. When this happened, they started to clump into twos and threes, forming ordinary protons, neutrons, π -mesons, and other particles. The corresponding anti-quarks also clumped to form anti-protons, anti-neutrons, anti- π -mesons, and so on.

As the Universe cooled further, the photons, whose gas stays at the same temperature as the particles because they collide frequently, no longer have enough energy to create proton-anti-proton pairs when they collide. At this point, there are still lots of collisions where protons and anti-protons annihilate to form photons, but the photons get redshifted by the expansion of the Universe and, by the time they meet other photons, no longer have enough energy to create protons and anti-protons

again. This also applies to neutrons and anti-neutrons. The number of particles decreases steeply at this point because annihilations are dominant over creations.

In principle, all the protons should have annihilated against all the anti-protons. But in fact, it is obvious that they did not: we are all made of protons that survived this era. It is natural, then, to expect that some anti-protons also survived, but this apparently did not happen. The two were so well mixed that we should see anti-protons everywhere, and we don't. Instead, it appears that there were simply more protons than anti-protons, by a small amount. This can only reflect a fundamental asymmetry in the laws of physics, a preference for one kind of matter against its opposite.

As the Universe expanded and cooled, the same thing happened later for the electrons: when the temperature was too small to create electron-positron pairs, then the electrons and positrons annihilated. The asymmetry at this point was exactly the same: the same laws of physics allowed the same fraction of excess electrons to survive as for protons.

We can learn how slight the excess of protons was by counting photons today. The microwave background radiation has on average 10^9 times more photons in any region of space than there are protons and neutrons. This number has not changed much since the separation of photons and electrons and the subsequent annihilations took place. The number of electrons has not changed, and the number of photons has changed only by a factor of two or so by the processes we describe below. It follows that the excess of protons/electrons over anti-protons/positrons in the very early Universe was about 10^{-9} . This is a small clue to the nature of laws of physics that physicists do not yet understand. We will return to this point in Chapter 27.

We owe our existence to this slight asymmetry in the laws of physics. If the laws were perfectly symmetrical between matter and anti-matter, then all the protons would have been annihilated in the early Universe, and there would have been nothing left to build stars, planets, and people from. The Universe would instead have been filled with pure radiation, cooling as it expanded.

It is interesting to reflect that we are formed from the waste that resulted from a slight imperfection in the laws of physics!

The Universe becomes ordinary

The annihilation of protons and neutrons stopped when the thermal energy kT fell to about the rest-mass-energy of a proton $m_p c^2$. It is easy to calculate that this temperature is about 10^{13} K. Since this temperature is smaller by a factor of 100 than the quark-soup temperature we quoted above, it follows that the mean photon energy had gone down by a similar amount, and therefore that the Universe had expanded by the same factor of 100. By Equation 25.1 on the next page, the time since the Big Bang had therefore increased by a factor of 10^4 , to 10^{-6} s.

The electrons annihilated at a temperature of about 6×10^9 K, when the Universe was a further factor of 1600 larger, and a factor of 3×10^6 older. It was now 3 s old. This is the epoch at which ordinary matter appears.

After the first microsecond, nuclear matter was already the normal material of which the nuclei of all elements is made. After the first three seconds, all the remaining exotic particles had disappeared, and the Universe was made of familiar stuff.

Notice how much physics takes place in times that seem short to us: everything really exotic is finished in the first three seconds! When one deals with the early

In this section: the excess protons and neutrons eventually dominated the composition of the early Universe, accompanied by electrons and neutrinos. Most other particles had gone away after the first few seconds.