How come the existence of matter in the Universe?

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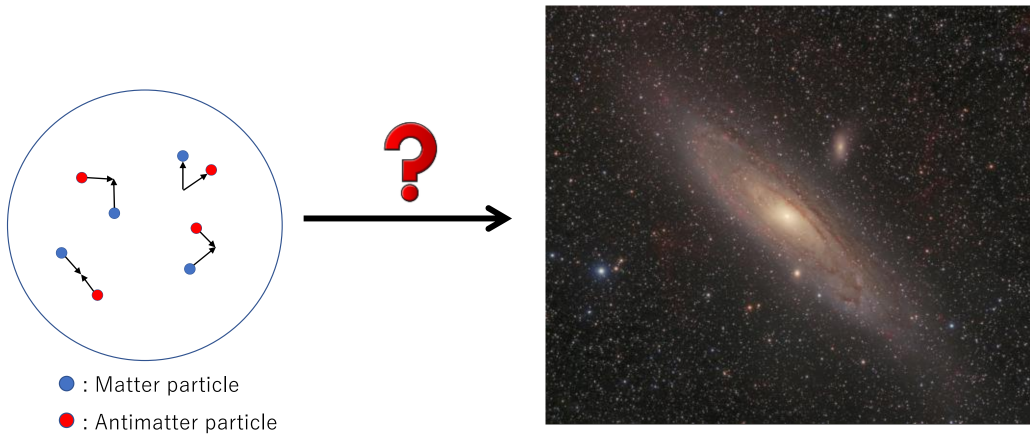

“How was the Universe born?”, “How does everything behave this way?”, “What is the element of all things?” We, human beings, have been attracted by these ultimately fundamental mysteries from the era of ancient Greece. It might be surprising to you, but the amazing development of particle physics and cosmology since the 1970s is now getting the heart of those mysteries.

In this essay, I explain one of those philosophical questions, “How come the existence of matter in the Universe?” from the viewpoint of particle physics and cosmology. After that, I introduce one of the most likely scientific scenarios, Leptogenesis, to solve this mystery.

To understand the origin of matter, we need to know about the early Universe where matter first appeared. Let me start with seeing what happened in the early Universe.

According to modern cosmology, our Universe exponentially expanded at the beginning. This rapid expansion of the Universe is called Inflation. Inflation eventually stopped 10^{-36} - 10^{-32} seconds after the birth of the Universe. After Inflation, the Universe started expanding relatively slowly.

It is after Inflation when matter was first generated. Matter was created as a pair with antimatter. Antimatter[1] is a particle whose mass is the same but whose charge is opposite to the corresponding particle. After the first creation, matter and antimatter were repeating their pair creation and pair annihilation.

Due to the expansion, the temperature of the Universe was going down. With the decline of the temperature of the Universe, the pair-creation of matter and antimatter came to be hard to occur, and many matter and antimatter were annihilated in pairs. Here is the point: Since matter and antimatter were created in pairs and annihilated again in pairs, if there had been no mechanism that made the gap between the amount of matter and antimatter in the early Universe, both would be depleted. The gap between matter and antimatter is called matter-antimatter asymmetry. Without this asymmetry generated in the early Universe, matter could not exist in today's Universe.

Now we found that the asymmetry between matter and antimatter is the key to the mystery of the origin of matter. Some mechanism must make matter-antimatter

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[1] When the particle and anti-particle are the same, the particle is called Majorana. Only chargeless particles can be Majorana particles.

asymmetry in the early Universe; this asymmetry made matter remain after almost all matter and antimatter annihilated in pairs and now results in galaxies, the earth, and ourselves. Therefore, we can rephrase the original question "How come the existence of matter in the Universe?" to "How did the matter-antimatter asymmetry generated in the early Universe?". In particle physics and cosmology, this problem is known as the matter-antimatter asymmetry problem. From the next paragraph, I want to explain one of the most likely solutions, Leptogenesis.

Leptogenesis was proposed by Fukugita and Yanagida in 1986[1]. Because this scenario is based on the Standard Model, let's see the Standard Model as the starting point.

The Standard Model is the cornerstone of modern particle physics. It describes all physical laws (except for gravity) and the fundamental constituents of matter. The Standard Model was established in the 1970s. Since then, it has been passing through many quantitative tests. Its astounding agreement with experiments is regarded as a huge success in particle physics. Now the Standard Model is accepted by almost all physicists.

As you may have heard of that, an atom consists of a nucleus and electrons; a nucleus consists of protons and neutrons; a proton and neutron consist of quarks. This is the Standard Model. In the Standard Model, the fundamental constituents of matter are quark and lepton[2]. Here, lepton is an electron-like group of elementary particles. Leptons are classified into two groups, charged leptons (including electrons) and neutrinos. These elementary particles have their antiparticles. Antiparticles of quarks are

[2] As you may notice, Leptogenesis is named after lepton.

antiquarks and those of leptons are antileptons.

Despite the success of the Standard Model, there are some problems in nature that the Standard Model cannot explain. The matter-antimatter asymmetry problem is one of them. Thus, we need to extend the Standard Model to solve our problem. Leptogenesis is an example of such extensions.

Now let's see Leptogenesis. In Leptogenesis, new particles are added to the Standard Model's particles. Those additional particles are called "right-handed neutrinos"[3]. These new particles decay into the Standard Model particles in the early Universe. The decay has two types. One is to lepton, and another is to antilepton[4]. The key point is that the decay rates of right-handed neutrinos to lepton and antilepton are slightly different. The different decay rates make the different amounts of lepton and antilepton. This is the mechanism to generate matter-antimatter asymmetry in the Leptogenesis scenario. The gap between lepton and antilepton is transmitted to the gap between quark and antiquark via a process[5] within the Standard Model. Then, the gap ultimately becomes the beautiful heavenly body in the Universe.

Leptogenesis is one of the most promising scenarios to explain the asymmetry in the Universe. It is known that the same model (the Standard Model plus right-handed neutrinos[6]) can also solve another puzzle of particle physics[7]. Although Leptogenesis has not yet been proven experimentally, searchings[8] for a clue of Leptogenesis are now under intense competition in the world. Some signs can be possibly found in 10 years.

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[3] For now, "right-handed neutrino" is just a name, and we don't need to care about the meaning of "right-handed" and their relationship with the Standard Model's neutrinos. Besides, these new particles are assumed as Majorana, but you can just also ignore this condition.
[4] Strictly speaking, Higgs also appears as the result of these decay processes.
[5] This is called the Sphaleron process.
[6] These are Majorana as well as in Leptogenesis.
[7] It is about the origin of the tiny masses of neutrinos. I won't explain it in this essay.
[8] For example, there is research trying to detect neutrinoless double beta decay.

The ultimate fundamental question “How come the existence of matter in the Universe?” is quite attractive. The answer to this question is now within our reach. The science steadily developed by many scientists over many years is now getting to the bottom of the mystery.

Reference

[1] M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986), 45-47.