The Mystery of the Asymmetry between Matter and Antimatter in the Universe

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Let's consider a coin tossing game. You toss a coin that has a 50-50 chance of landing on its head or its tail. If you toss the coin enough times in exactly the same way, you will have almost the same number of head cases and tail cases. However, what happens if there is something affecting the coin, like wind or a tremble of your hand? The result will be different and you may get many more heads than tails or the other way around. The same thing has happened in our universe, and this has led to the fact that the amounts of matter and antimatter are not equal.

Do you know what antimatter is? All visible matter in the universe is made of fundamental building blocks, called elementary particles. Furthermore, the elementary particles composing matter are classified into two groups: quarks and leptons. For example, a hydrogen atom is composed of one proton comprising three quarks and one electron, which belongs to the lepton particle family. Also, neutrinos are neutral leptons. For each lepton or quark, there is an antiparticle that has exactly the same mass as its counterpart particle and the opposite electric charge. A substance which is composed of antiparticles is called antimatter. For example, a positron is the positively charged antiparticle counterpart to the negatively charged electron. While their charges are opposite, they share the same mass value. Particle and an anti-particle are always generated as a pair, and when they come in contact, they annihilate one another. In the early universe, the initial expansion called the Big Bang should have created the same amount of matter and antimatter. Thus, if the physics laws between matter and antimatter is symmetric, the amount of matter and antimatter should be the same. However, in the current universe, almost all things consist of only matter and no one can answer why.

This imbalance between matter and antimatter is one of the biggest unsolved problems in physics. Its solution would give us a more detailed understanding of the universe and how it has grown. Furthermore, this question is crucial to our existence. Because, if it were not for this mysterious matter-antimatter asymmetry, we would not even exist in this world!

In 1967, Sakharov revealed that three conditions are required in order to explain this imbalance. These three “Sakharov conditions” are:

1) There must exist an interaction that violates the baryon number conservation.

2) There must be an interaction that violates C & CP symmetries.

3) The interaction must go out of the thermal equilibrium.

A baryon is a composite subatomic particle that contains an odd number of quarks. For example, a proton consists of 2 up-quarks and 1 down-quark, and neutron consists of 1 up-quark and 2 down-quarks. A baryon is defined to have a baryon number of 1 and an antibaryon, which is composed of 3 antiquarks, has a baryon number of -1. Thus, the first condition of Sakharov is necessary to produce an excess of baryons to antibaryons.

The second condition is about charge conjugation (C) and parity (P) symmetries. CP symmetry states that the laws of physics must be the same if a particle is interchanged with its antiparticle and its spatial coordinates are inverted at the same time. This condition is also needed so that the interactions which create more particles than antiparticles will not be counterbalanced by the interactions which create more antiparticles than particles. The third condition is a little bit technical but it indicates that there must not be a compensation between processes increasing and decreasing the baryon number. In this way, we can explain how the asymmetry between matter and antimatter occurred and grew.

Related to this second condition, CP violation in the quark sector was devised and it was later experimentally confirmed. It is also expected that CP violation occurs in the lepton sector, such as neutrino cases. A phenomenon called "neutrino oscillation" is the key to measure CP violation in neutrinos. There exist three types of neutrinos;

electron neutrinos, muon neutrinos and tau neutrinos (and their counterpart antineutrinos). These classifications are referred as neutrino's "flavor." It is known that a neutrino with a given flavor, after traveling a certain distance, will transform into another flavor. This probabilistic phenomenon is the neutrino oscillation.

There are several experiments in the world searching for CP violation in the lepton sector via precision measurement of neutrino oscillation. The T2K experiment, a long-baseline neutrino oscillation experiment conducted in Japan, is a very promising one. It produces muon neutrinos at J-PARC (Japan Proton Accelerator Research Complex) in Ibaraki prefecture and detects them at the detector "Super-Kamiokande" in Gifu prefecture. Super-Kamiokande is located 295 km away from J-PARC. Neutrinos change their flavor while traveling from J-PARC to Super-Kamiokande. By measuring neutrino oscillation probabilities with both neutrinos and antineutrinos separately, one can determine if their CP symmetry is violated. The T2K experiment has found strong evidence of the CP violation via a precise measurement of neutrino oscillations [1]. The existence of CP violation in neutrino oscillation is a key to reveal the mystery of asymmetry between matter and antimatter in the universe.

Figure: Overview of the T2K experiment (from https://higgstan.com/4koma-t2k/)

[1] Abe, K., Akutsu, R., Ali, A. *et al.* “Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations”. *Nature* **580,** 339–344 (2020).