

Leptogenesis: A non-relativistic study

Tobias Theil

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1. Introduction

[...] One way to describe the observed baryonic asymmetry is by postulating, that the universe has been in an asymmetric state just from the beginning and that the matter and antimatter is concentrated in big domains throughout the universe, which come into contact just at their outer borders. Technically there is no reason for the universe not to have started in an asymmetric state, in that case one would measure high gamma rates due to the matter-antimatter-annihilation right between these distinct regions.

Since there is no kind of such radiation seen, patches of different kinds of matter have to be as big as the presently observable universe. Because this doesn't seem very plausible, so the baryonic asymmetry had to arise dynamically from an universe where matter and antimatter existed in the same amounts.

[...]

2. Outline of baryogenesis

Actually in 1967 the Soviet physicist Andrei Sakharov postulated the criteria, which have to be met in order for an excess of baryons over anti-baryons to be generated out of a fully symmetrical universe.

2.1. Sakharov Conditions

As mentioned above there are three crucial properties of nature, the Sakharov conditions, which are required to produce a net baryon number greater than zero. These three conditions are:

1. B-violating process(es)
2. C and CP violation
3. Departure from or loss of thermal equilibrium

For a general insight of these three conditions the first one will be skipped, since it is quite obvious, that in a totally symmetric universe there has to be at least one B-violating process in order to cause an imbalance in matter and antimatter.

The general importance of the other two will be discussed in the following.

2.1.1. C and CP-violation

Charge conjugation (C), parity (P) and their combination (CP) are two or more specifically three basic symmetries of the universe. C symmetry states, that physical processes are the same, even after exchanging particles for their respective anti-particles, while P-symmetry guarantees invariance under the transformation $\vec{r} \rightarrow -\vec{r}$. CP symmetry then simply is a sequence of a C followed by a P transformation.

To explain why C has to be violated for baryogenesis being possible, consider the B-violating reaction

$$X \rightarrow Y + B \tag{2.1}$$

with X and Y particles with B=0 and B representing the excess baryons. This reaction happens with a certain rate, which is, using C as a symmetry, just the same as the reaction rate for the conjugate process.

$$\Gamma(X \rightarrow Y + B) = \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B}) \tag{2.2}$$

Eq. 2.2 implies, that under C exactly the same amount of baryons and anti-baryons will be produced and therefore no excess baryons are left after the annihilation. This means C must be

violated.

But additionally to this CP violation is essential for baryogenesis. To illustrate why, take a closer look at the also clearly B violating X decay with its two channels:

$$\begin{aligned} X &\rightarrow q_L q_L \\ X &\rightarrow q_R q_R \end{aligned}$$

with q an arbitrary quark. The subscripts L and R denote the the left - or right-handedness chirality of the decay products. CP then effects each particle as follows

$$\begin{aligned} X &\xrightarrow{CP} \bar{X} \\ q_L &\xrightarrow{CP} \bar{q}_R \\ q_R &\xrightarrow{CP} \bar{q}_L \end{aligned}$$

So CP doesn't just change matter for anti-matter, but the handedness of the particles as well. So if CP holds as a symmetry the consequences for the reaction rates are:

$$\Gamma(X \rightarrow q_L q_L) = \Gamma(\bar{X} \rightarrow \bar{q}_R \bar{q}_R) \qquad \Gamma(X \rightarrow q_R q_R) = \Gamma(\bar{X} \rightarrow \bar{q}_L \bar{q}_L)$$

Adding these two results in

$$\Gamma(X \rightarrow q_L q_L) + \Gamma(X \rightarrow q_R q_R) = \Gamma(\bar{X} \rightarrow \bar{q}_R \bar{q}_R) + \Gamma(\bar{X} \rightarrow \bar{q}_L \bar{q}_L) \quad (2.3)$$

Eq. 2.3. implies, that as long as there are as many particles X as anti-particles \bar{X} in the initial state of the universe, which is just the starting point of the modell the Sakharov conditions try to describe, there can only be an asymmetry between left and right-handed particles be achieved, but that isn't a baryon asymmetry, which is clearly needed for baryogenesis. CP must be violated. Shortly summarized the bottom line here is, that the existence of B-violating processes is not sufficient for baryogenesis, but that there also has to be C and also CP violation, since without this kind of symmetry breaking any baryonic excess would be washed out by the corresponding C or CP conjugated process, as shown with the simple examples above.

2.1.2. Departure from thermal equilibrium

2.2. Baryogenesis in the Standard Modell

2.2.1. Electroweak baryogenesis

2.2.2. Failures of the SM

3. Outline of leptogenesis

3.1. Expandig the SM

4. Non-relativistic leptogenesis

5. Summary

A. Appendix

References