Electroweak Phase Transition and Baryogenesis

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Abstract

Our universe is apparently matter dominant. Although CP violation is experimentally proven, the full scenario of baryogenesis remains to be unsolved. Matter asymmetry is discussed briefly in this paper and electroweak phase transition (EWPT) is presented as one possible scenario of baryogenesis. Bounds on the Higgs boson mass for such scenario for Standard Model (SM) and Minimal Supersymmetric extension to Standard Model (MSSM) is discussed. It will be discussed that the LEP experiment has excluded SM as the possibility for matter asymmetry scenario and thus requires new physics beyond SM to explain baryogenesis through EWPT.

1 Introduction

Since the discovery of antiparticles [1], it has been very clear that the matter and antimatter symmetry is one of the most prominent symmetry in particle physics. However like all symmetries in physics, interesting things happen when these symmetries are broken. One example that will be discussed in this paper is the baryogenesis. Various baryogenesis scenarios explain how there are more matter than antimatter in this universe. Certainly understanding baryogenesis would be important as it would answer how anything in this universe came about and therefore be a crucial part of understanding cosmology.

In particle physics there are discrete symmetries considered to be closely related to matter and antimatter symmetry.[1] The so called CP-symmetry is the symmetry that particle physicists are interested in. The reason why CP-symmetry is considered for matter and antimatter symmetry and not simply C-symmetry is because of the fact that only left-handed neutrino and only right-handed antineutrino were observed. Hence, in order to fully consider the problem of matter and antimatter symmetry, not only C-symmetry but also CP-symmetry needs to be considered.

Although C-symmetry was broken maximally by the fact that all neutrino observed are left-handed, It was believed in the physics community that CP-violation was a true symmetry. [2] However, CP violating process in the neutral K meson system was observed [3] during 1960s, and so this came as a surprise to the particle physics community. However, shortly after the discovery it was argued by Sakharov that CP violation should not be taken as a surprise as it is one of necessary conditions for baryon asymmetry to exist in our universe. [4] (*i.e.* CP-violation is a necessary condition for us to exist.) These conditions will be discussed shortly. Since then baryogenesis became one of central question in physics and is yet to be answered.

1.1 Baryon Asymmetry in Universe (BAU)

Despite our naive perception of the symmetry between matter and antimatter, our universe seems to be matter dominant. Although we can never conclusively prove that there are more matter than antimatter in the universe as a whole, there are many indirect proofs that it is in fact the case. As a simple evidence, we do not observe any everyday proton anti-proton annihilation in our body. For more concrete evidence, one can look at the data from the Wilkinson Microwave Anisotropy Probe(WMAP). The amount of matter dominance measured through WMAP data is, [2]

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10} , \tag{1}$$

[1] One is the charge conjugation symmetry (C-symmetry) and the other is the parity symmetry (P-symmetry). The combined symmetry of the two is called, CP-symmetry. The C operator switches particle with its antiparticle partner. The P operator inverts the coordinate system from (x, y, z) to $(-x, -y, -z)$.

which is a tiny fraction. Here, n_B is the number of baryons, $n_{\bar{B}}$ is the number of anti-baryons, and n_γ is the number of photons in the universe. This number may not seem large but this tiny fraction of excess is what consists of everything we see in the universe: us, the Earth, and all the stars and galaxies.

One might ask if there are large chunk of antimatter somewhere else hiding in the universe. This was investigated and indeed we did observe some evidence of antimatter in our current universe through cosmic rays. However the amount of antimatter we observe is consistent with the secondary production through process like, $p+p \to 3p+\bar{p}$. [5] Besides, if there were significant amount of antimatter coexisting outside of our solar system, but in the galaxies, one would detect γ rays from matter antimatter annihilations, but this is not the case. [6] In more recent publication, it argues that if there was a large domain of antimatter, the annihilation induced at the interface between matter and antimatter will diffuse γ rays which would then be observed by through cosmic microwave radiation. However no such observation was made and quantitatively the result safely puts the size of matter dominance as of the order of Hubble size. [7] So how did the matter come about from a symmetric universe?

One might naively answer to this question by assuming from that the universe started with matter dominant universe and hence the current universe has more matter than antimatter. Although this would explain away everything but as physicists believe that the universe started from a singularity through big bang, it is logically more simple to assume that the the whole entity was purely energy. Hence, we conclude that the universe must have started with a symmetric universe, and as the universe expanded and cooled down some symmetries were broken and more matter was produced than the antimatter.

The main topic of this paper is to discuss what possible scenario could the nature have taken in generating more matter over antimatter. Particularly electroweak baryogenesis will be discussed as one such possible scenario. In this scenario, the electroweak theory with multiple vacua undergoes a phase transition which is in first order, and the matter is produced by overall Baryon number violating processes.

2 Sakharov Criteria

After the CP violating process has been observed, few years later, Sakharov listed out the necessary conditions for a theory to be able to undergo baryogenesis. [4] They are referred to as Sakharov criteria. They are as follows:

- Baryon number (B) symmetry violation.
- C symmetry and CP symmetry violation.
- Significant departure away from thermal equilibrium.

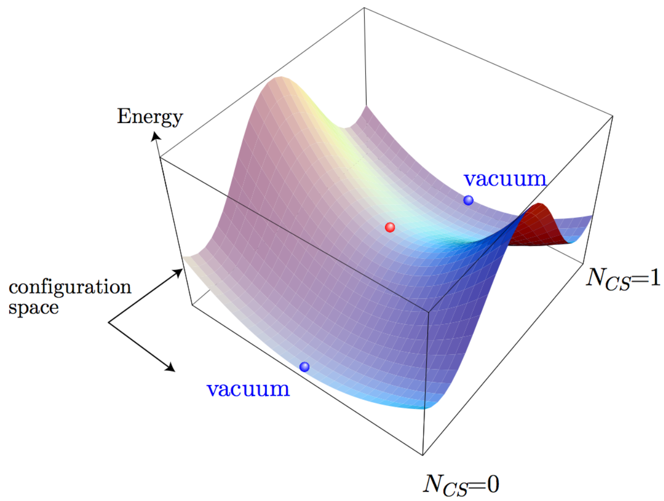

Figure 1: Figure that show different vacua. These different vacua have different N_{CS} values.[8]

The first condition baryon number symmetry violation is obvious as without baryon number symmetry violation, no matter can ever be produced more than antimatter. Therefore, with the symmetric initial condition there is no possible way of creating more matter than antimatter. In the same way, the second condition is necessary because if C and CP symmetry is not violated, any process that creates more matter will have a symmetric process the creates exactly the same amount of antimatter. Therefore the net baryon number is going to stay the same. In order to increase the total number of baryons, therefore the theory must violate C and CP violation. The third criteria is to ensure that such processes that treats matter and antimatter differently will eventually raise the net baryon number in thermal equilibrium. Normally given that the CPT symmetry is true, the thermal equilibrium of the baryon number operator is [2]

$$\langle B \rangle = 0 \ , \tag{2}$$

where the expectation value is over the thermal equilibrium average. Therefore, in thermal equilibrium there is no net generation of baryons. Hence, it must be that any baryon-generating theory should be able to push the system away from its thermal equilibrium enough so that net average baryon number would not equal to zero and hence generate baryons. So how does Standard Model electroweak theory satisfies these conditions? In following sections I will discuss each Sakahrov criteria in electroweak theory scenario, mainly focusing on the first and the third criteria. The second criteria will not be discussed in this paper as CP violation is already been confirmed by experiment and well understood by theory as well.

3 Standard Model: Electroweak Theory

3.1 Baryon number violation in Electroweak theory

The standard model electroweak theory is based on Yang-Mills Theory. The gauge group of electroweak theory is, $SU(2) \times U(1)$. Such a theory would have the Lagrangian given as,

$$\mathcal{L} = (D_\mu \phi)^\dagger D^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + V(\phi) + \mathcal{L}_f \ , \tag{3}$$

where the $F_{\mu\nu}$ is the field strength of the $U(1)$ gauge group with the hypercharge and the $W^a_{\mu\nu}$ is the field strength for the $SU(2)$ gauge group with the weak isospin. Here we then add the Higgs field, ϕ. The Higgs potential is,

$$V(\phi) = \frac{\lambda}{4} (\phi^\dagger \phi - v^2)^2 \ . \tag{4}$$

where the vacuum expectation value is, $v = 246\,\mathrm{GeV}$. In this theory the vacuum is degenerate. The construction of theory through perturbation around different vacua will be equivalent to each other. This is because different vacua are connected by gauge transformation. However, different vacua have different so-called, Chern-Simons number N_{CS}, [2]

$$N_{CS}(t) = \frac{g^2}{32\pi^2} \int d^3x \, \epsilon^{ijk} \mathrm{Tr} \left(A_i \psi_j A_k + \frac{2}{3} i g A_i A_j A_k \right) \ . \tag{5}$$

where, A is the gauge field for $U(1)$ group in the electroweak theory. The detailed derivation of the above expression is not in the scope of the paper. However it is important to understand that for different vacua the N_{CS} are different. The N_{CS} value is not gauge invariant, however the difference of Chern-Simons number, ΔN_{CS} between different vacua is a gauge invariant quantity. In *chiral* theory, where one example would be the electroweak theory in Standard Model, it is precisely this quantity that is related to the baryon number difference when quantum effects are considered, [2] (which will be explained shortly)

$$\Delta B = \Delta N_{CS} \, . \tag{6}$$

Therefore, if the system were to undergo such a transition through the vacua the net baryon number can change. (see Figure 1.) However, classically the electroweak theory has exact global baryon number symmetry and hence it would mean that no such transition can occur. However, when such *chiral* theory is considered as quantum theory the story turns out more promising. The vector current associated with quarks can be written as,

$$j^\mu_B = \frac{1}{2} Q \gamma^\mu Q \ , \tag{7}$$

where Q represents the quark fields and the color and flavor indices are implied. This current in classical level conserves the baryon number and will not have any interesting features. However, any axial current $\psi \gamma^\mu \gamma^5 \psi$ is anomalous because of the quantum effects.

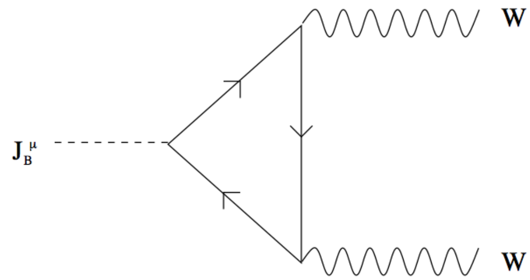

Figure 2: Feynman diagram contributing to the anomaly in baryon number conservation

[9] In fact, electroweak theory is a *chiral* theory. The coupling of the fermions to the gauge fields is,

$$j^{\mu}_{B} = \frac{1}{4}[Q\gamma^{\mu}(1-\gamma^{5})Q + Q\gamma^{\mu}(1+\gamma^{5})Q] \ , \tag{8}$$

which includes the axial current and therefore could induce desired result through quantum effect. Figure 2. shows the anomalous current. In fact, due to this anomalous term, it turns out that the baryon number difference is Eq. (6). Hence, the change in baryon number is directly related to the change in Chern-Simons number.

Using this quantity the rate of which the tunneling between vacua happens can be calculated. At zero temperature, the rate is [2]

$$\Gamma(T=0) \sim 10^{-170} \ . \tag{9}$$

However, this amount is too little to accommodate the whole matter antimatter asymmetry. In non-zero temperature, the thermal fluctuation can cause the system to hop over between vacua and give more contributions to the matter antimatter asymmetry. Especially when the temperature is around the critical temperature of the electroweak phase transition where the Higgs vacuum expectation value is non-zero, this hopping over different vacua could have happened more rapidly due to thermal fluctuation and result in net baryon number excess. [2]

3.2 Electroweak Phase Transition

As it was alluded before the system has to be driven away from the thermal equilibrium in some way to ensure the net baryon number asymmetry. Just like in usual phase transition theory, in first order transition the order parameter changes abruptly.

In the same way in electroweak baryogenesis scenario, it is argued that the electroweak phase transition happened in first order. As the temperature of the universe cooled below the electroweak scale, the spontaneous symmetry breaking in electroweak theory caused the separation in two region of true vacuum and false vacuum. where, one region is the broken phase and the other the unbroken phase as shown in Figure 3. When the bubble

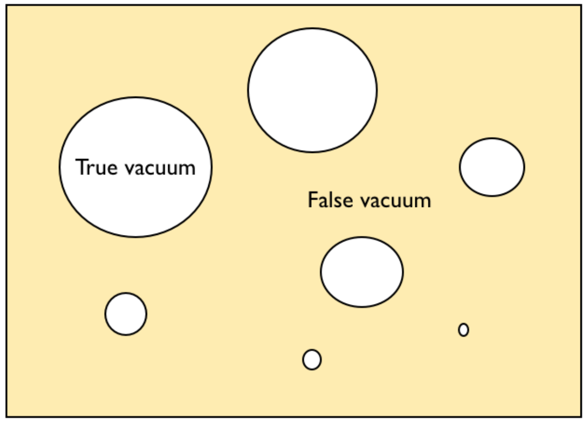

Figure 3: The nucleation of true vacuum happens as a bubble. When the bubble is large enough the bubble will grow and merge with other true vacuum and transition the whole space into true vacuum. In the boundary the order parameter value ϕ abruptly so it can be pushed far away from equilibrium.

of true vacuum of size that is bigger than the critical bubble size starts to expand, as the bubble interface passes through each point in space, the order parameter and the fields change abruptly to reflect the true vacuum. At these interface the system can be pushed significantly away from the thermal equilibrium. In this way the third Sakharov criteria can be satisfied. Then as the false vacuum turns into true vacuum, at the interface, baryon number violating process occurs causing baryogenesis. When the region of space is now in true vacuum the baryon violating process is highly suppressed and the net baryon number is now "frozen". [2] In other words, if this picture were to be true, it may be that our existence in this universe may be just like the air bubbles in a boiling water.[2]

4 Beyond Standard Model

After such process has occurred and when the space is in true vacuum state, the baryon violating process has to be highly suppressed to prevent any *washout* of net baryon number. Requiring this condition results in bounds on the mass of the Higgs. In electroweak baryogenesis the bounds on the Higgs mass is, [11]

$$m_H < 90\,\mathrm{GeV}\ . \tag{10}$$

However this region of parameter is already been excluded by LEP experiment. [12] Hence, Standard Model cannot account for the whole baryogenesis through electroweak phase transition. Therefore one has to look for some other way of electroweak baryoge-

[2] One time I was boiling water to prepare food and thought about this analogy (aside from the fact that it is boiling instead of cooling) and said to myself, "we are nothing but the air bubbles."

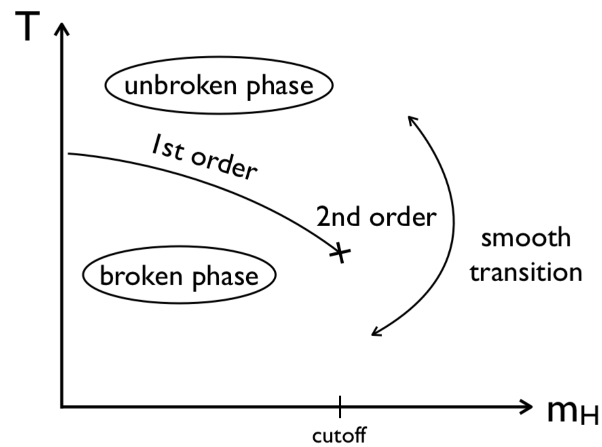

Figure 4: Phase diagram of electroweak theory is shown here. Beyond certain mass of the Higgs the theory is no longer in 1st order phase transition and hence electroweak baryogenesis picture fails. In order for electroweak baryogenesis to be a viable scenario EWPT has to be a first order transition.[10]

nesis. Some extensions to the scenario involves, Two-Higgs-Doublet model, Minimal Supersymmetric Standard Model (MSSM), or non-Minimal Supersymmetric Standard Model (nMSSM). I do not discuss in detail how these scenarios proceed in explaining the electroweak baryogenesis however, I present their relevant findings of bounds on the Higgs mass. In MSSM the bounds on the Higgs mass and the stop mass to be, [13]

$$M_H \lesssim 127\,\mathrm{GeV}\ , \quad \tilde{t} \lesssim 120\,\mathrm{GeV}\ , \tag{11}$$

which is still a possibility.

The LEP experiment is now closed however, in ATLAS or CMS experiment, at the LHC, physicists are further searching for the Higgs boson. With their preliminary results, major parameter region of Higgs boson has been excluded. [14] However there are still unexcluded mass parameter region where MSSM may be a viable option.[3] If ATLAS or CMS experiments find that the mass of the Higgs is within the bounds of the Higgs mass, the next thing to do is to look for the superpartner of top quark, stop, $\tilde{t}$. However so far MSSM has not been looking promising in ATLAS experiments.

5 Conclusion

In this paper, first simple matter antimatter asymmetry was mentioned and basic electroweak baryogenesis idea has been laid out. In order for baryogenesis to be possible three Sakaharov criteria needs to be satisfied, and it has been discussed that the Standard Model

[3]As of December 13th, 2011, the most likely value of mass of the Higgs is ~ 125 GeV.

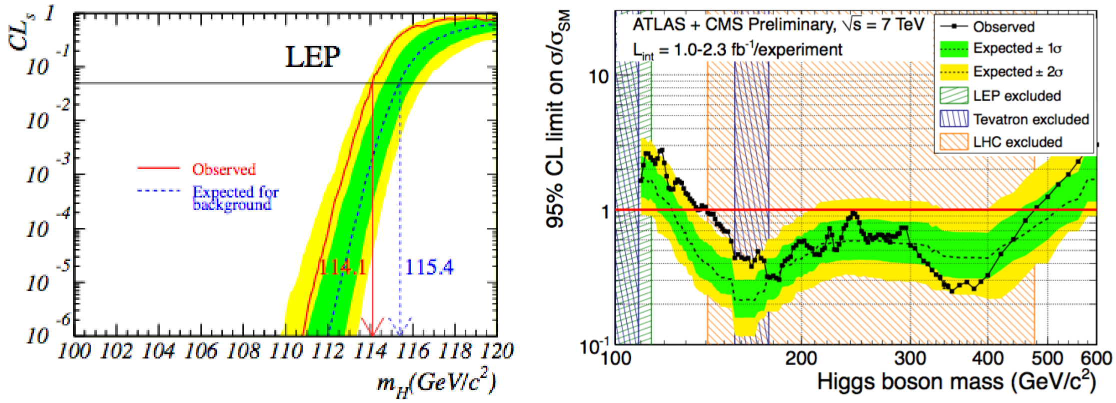

Figure 5: Large Electron-Positron(LEP) collider experiment excluded Higgs boson of mass below 114.1 GeV with 95% confidence limit.

satisfies the three conditions. However, as LEP experiment excluded the possible Higgs boson mass for electroweak baryogenesis to happen in the Standard Model some extension to the Standard Model may be necessary to explain the it may be possible to explain baryogenesis. It is interesting that from cosmological point of view gives hint that the beyond Standard Model is necessary.

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