Electroweak phase transition in the early universe and Baryogenesis

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Abstract

In the Standard Model, it is generally accepted that elementary particles get their masses via the Higgs mechanism, which involves a phase transition from the symmetric phase at higher temperatures (close to the Big Bang) to a phase in which the symmetry has been spontaneously broken. One of the outstanding problems in particle physics is to explain the origin of the observed matter-antimatter asymmetry (baryogenesis) which we observe in today's universe. In this term paper, we look at the phase transition associated with the Higgs mechanism and attempt to explain the above asymmetry using the same. If the phase transition is "first-order" and rapid, it is possible to obtain the observed asymmetry from this model.

1 Introduction

The Standard Model of particle physics, probably the most well-tested theory in physics, was written out in its final form somewhere in the middle of the 1970's. The underlying local gauge group of the model is $SU(3)_c \times SU(2)_L \times U(1)_Y$. Here c refers to the color charge of quarks, L denotes the left handed fermions, while Y represents the hypercharge (a quantity analogous to, but not the same as the electric charge). The $SU(3)_c$ part of the symmetry group deals with gluons and their couplings to quarks, thus giving rise to the field of QCD. In this paper, we will concentrate on the remaining $SU(2)_L \times U(1)$, or the electroweak part of the gauge group, which turns out to be the relevant part in the discussion of the electroweak phase transition.

Even though the gauge group of the Standard Model is $SU(2)_L \times U(1)_Y$, we do not observe $SU(2)$ symmetry at everyday energy scales. On the other hand, we are all familiar with an example of a $U(1)$ gauge field, the electromagnetic field. What then, happened to the $SU(2)$ part of the symmetry? Another issue, which is tied in with the previous one, is that if one constructs the Standard Model from just fermions and gauge fields, there is no way of inserting mass terms into the Lagrangian without violating the underlying symmetry. However, we know that not only do fermions - such as electrons and quarks - but also certain gauge fields - such as the gluons - have mass. So how does one make the Standard Model work so that it can describe massive particles?

Consider another apparent roadblock to the Standard Model, coming from observations at the largest of length scales. As far out into the Universe as we can see, it seems that all structures are made out of matter, as opposed to antimatter. The Standard Model, on the face of it, seems to tell us that there should be no surplus of matter over antimatter, or vice-versa. Once again, we seem to be faced with a conflict between the Standard Model and observation.

The phenomenon of symmetry breaking and phase transitions can help provide a solution to all the three problems that we have outlined above. The assumption of spontaneous breaking of the $SU(2)_L \times U(1)_Y$ symmetry to a $U(1)$ symmetry allows us to formulate a consistent mechanism for particles to acquire masses. If the associated phase transition is first order and rapid, then this symmetry breaking can also lead to the large baryon asymmetry that is observed. In Section 2, we shall formulate the mechanism of spontaneous symmetry breaking for the $SU(2)_L \times U(1)_Y$ group. We shall also see how it gives rise to massive fermions and gauge bosons. In Section 3, we look at the the conditions required to produce large baryon number asymmetries. We then look at how electroweak symmetry breaking provides us with the correct ingredients for the asymmetry to develop in the early universe, soon after the Big Bang. Finally, in Section 4, we review the main points of the paper, and discuss certain further developments in the field.

2 Spontaneous Electroweak Symmetry Breaking

As mentioned in Section 1, we will consider the breaking of symmetry in the $SU(2)_L \times U(1)_Y$ part of the theory. The relevant Lagrangian can be written as

$$
\begin{aligned}
\mathcal{L} = & - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{L}\gamma^\mu \left(i\partial_\mu - \frac{g}{2} W^a_\mu \tau^a - \frac{g'}{2} B_\mu Y \right) L \\
& + \bar{R}\gamma^\mu \left(i\partial_\mu - \frac{g'}{2} B_\mu Y \right) R + \left| \left(i\partial_\mu - \frac{g}{2} W^a_\mu \tau^a - \frac{g'}{2} B_\mu Y \right) \phi \right|^2 \\
& - V(\phi) - \left(\lambda_u \bar{q}_L \phi^C u_R + \lambda_d \bar{q}_L \phi d_R + \lambda_e \bar{l}_L \phi e_R + h.c. \right) , \qquad (1)
\end{aligned}
$$

where $W^a_{\mu\nu}$ is the field strength tensor of the $SU(2)_L$ gauge field W^a_μ and τ^a are the generators of $SU(2)$ in the fundamental representation. Similarly, $B_{\mu\nu}$ is the field strength tensor of the $U(1)_Y$ Abelian gauge field with hypercharge Y. L stands for the left handed fermions, whereas R stands for right handed fermions. As one can clearly see from the form of the Lagrangian, the Standard Model has a left-right asymmetry because the right handed fermions do not couple to the $SU(2)_L$ gauge field. The left handed fermions therefore are doublets of $SU(2)_L$ whereas the right handed fermions are singlets. Apart from the fermions, there is also a scalar field ϕ which is a doublet of $SU(2)_L$. The scalar field has a polynomial potential $V(\phi)$ which we leave unspecified for the moment. There are also couplings -whose strengths are given by the parameters λ_d, λ_u and λ_e - which lead to interactions between the right handed fermion singlets (the up and down quarks), the left handed fermion doublets and the scalar field. It is important to notice that there are no explicit mass terms which would have violated the symmetry of the theory. We have not specified the hypercharge eigenvalues for the fermions and the scalar field. However, this can be worked out from the fact that the Lagrangian should be a scalar under both $SU(2)_L$ and $U(1)_Y$. Another small point worth noting is that we have not included right handed neutrinos in the Lagrangian.

To see how the symmetry of this Lagrangian can be spontaneously broken, we look at the potential of the scalar field, given by $V(\phi)$. We assume,to the lowest order, that it is a polynomial in ϕ with coefficients which are only constrained by the overall symmetry of the Lagrangian. Therefore, for given values of coefficients, we can find the minimum of the potential, which gives us the vacuum of the theory. It should be remembered though, that ϕ is a $SU(2)$ doublet and not a number. Hence it is defined by four real numbers. Due to symmetry considerations, the first term in the potential must be quadratic, and we have only even powers of ϕ at the lowest order. The coefficient of the highest order term in the potential should be positive so that we have a potential which is bounded from below.

If we look at the case where all coefficients are positive, we get the trivial vacuum where all components of $\phi = 0$. There cannot be spontaneous symmetry breaking in this case. However, if we consider a case where the coefficients can be either positive or negative, we can have a situation where the minima of the potential lies not at $|\phi|^2 = 0$, but at some finite value of $|\phi|^2$. We have one equation and four real parameters. This means that we are free to choose three of them. This choice is what leads to symmetry breaking in the system. The choice of the three free parameters determines the vacuum of the system. Since $SU(2)$ is a continuous symmetry, we have infinitely many possible vacuua. It is convenient to choose

$$\phi_{vac} = \begin{pmatrix} 0 \\ v \end{pmatrix} . \tag{2}$$

This vacuum does not respect the $SU(2)_L$ or $U(1)_Y$ symmetry, but instead has a new $U(1)_C$ symmetry, where C denotes the electromagnetic charge that we are familiar with. If we now look at the effective Lagrangian after having substituted ϕ_{vac} into it, we see terms which start resembling the mass terms of fermions and gauge fields.

If we look at the kinetic term involving ϕ in Eq. (1), the derivative term goes away because ϕ_{vac} is a constant in space and time, and only the gauge couplings remain. The term can be written explicitly as

$$\begin{aligned} \left| \left(-\frac{g}{2} W^a_\mu \tau^a - \frac{g'}{2} B_\mu Y \right) \phi_{vac} \right|^2 &= \frac{1}{2} \left(\frac{1}{2} g v \right)^2 |W_1|^2 + \frac{1}{2} \left(\frac{1}{2} g v \right)^2 |W_2|^2 \\ &+ \frac{1}{8} v^2 \begin{pmatrix} W_3 & B \end{pmatrix} \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W_3 \\ B \end{pmatrix} . \end{aligned} \tag{3}$$

The first two terms on the RHS of Eq. (3) are like mass terms for the W_1 and W_2 gauge bosons, since masses appear as coefficients of quadratic terms in the Lagrangian. These are the charged $W^\pm$ bosons which appear in high energy physics. The third term does not yet look a term we can interpret as a mass. We diagonalize it so that it becomes

$$\frac{1}{8} v^2 \begin{pmatrix} A & Z \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & g^2 + g'^2 \end{pmatrix} \begin{pmatrix} A \\ Z \end{pmatrix} , \tag{4}$$

where $A = \cos\theta_W B + \sin\theta_W W_3$ and $Z = -\sin\theta_W B + \cos\theta_W W_3$. The θ_W that appears in the equation is like a mixing angle and is given by $\theta_W = \tan^{-1} g'/g$. We see that a certain combination of W_3 and B gives rise to another massive vector field, the Z boson. However, there is another gauge field A_μ which remains massless, namely the photon of electromagnetism. So, instead of four massless gauge fields that we started with, we now have three massive and one massless gauge fields.

Now, we have to figure out how fermions masses arise from the spontaneous symmetry breaking. If we look back at the last line of Eq. (1), we see the coupling terms of the form $-\lambda_u \bar{q}_L \phi^C u_R$, $-\lambda_d \bar{q}_L \phi d_R$, and $-\lambda_e \bar{l}_L \phi e_R$. After spontaneous symmetry breaking, the ϕ field attains its vacuum expectation value, and the interaction terms now look like $m_u \bar{u}_L u_R$, $m_d \bar{d}_L d_R$, and $m_e \bar{e}_L e_R$. The masses are then directly proportional to strength of the couplings of various fields to the scalar field ϕ. These massive fermions are what observe in experiments.

In this section, we have seen a mechanism whereby gauge fields and fermions acquire masses without actually breaking the symmetry by hand. The mechanism involved the introduction of a new scalar field, often called the Higgs field, which has its own polynomial potential. The minima of this polynomial determine the vacuua of the theory, and depending on the value of $|\phi|^2$ at the minima we can have symmetry breaking and the generation of masses.

3 Baryogenesis

3.1 Conditions for baryogenesis

As mentioned in the introduction, observations at all length scales, from the smallest to the the largest, seem to show that there is a large matter-antimatter asymmetry in the universe. There seems to be very little antimatter present in the universe at today's energy scales. This asymmetry can be quantified by a number

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} , \tag{5}$$

where n_b and $n_{\bar{b}}$ denote the number of baryons and antibaryons per unit volume respectively, and n_γ denotes the number of photons per unit volume. Observations show that the value of this parameter should be of the order of 10^{-10}. On the other hand, looking at the Standard Model, there seems no obvious way in which to get a non-zero number for η unless the asymmetry already existed at the time of the Big Bang. However, this would violate naturalness, and is ruled out as an explanation for the observed asymmetry.

In 1967, Sakharov proposed certain conditions that any theory attempting to explain the asymmetry must satisfy. These three general conditions should be satisfied irrespective of the exact mechanism of an individual theory.

Firstly, the mechanism should have a way of violating the baryon number B, so that an excess of baryons over anti-baryons can be generated. This is obviously necessary if the mechanism is to explain the non-zero value of η, starting from $\eta = 0$ at the Big Bang.

Secondly, the Sakharov conditions state that the theory should also have CP violations. Unless the theory violates CP symmetry, then every B number violating process would have a counterpart in the anti-baryons, and the asymmetry would get out.

The third and final Sakharov condition is that the theory should provide for interactions taking place outside thermal equilibrium with the environment. Even if the theory is CP violating, it will not produce baryon number asymmetry in the long run if all interactions occur under conditions of local thermal equilibrium. This is because the theory should be CPT invariant and unless there is an arrow of time, interactions at thermal equilibrium will not be able to differentiate between baryons and anti-baryons, thereby washing out any excess.

A theory satisfying the three conditions above can produce a non-zero value of η. However, different models will, in general, predict different values of η depending on their specific mechanism. Therefore, for a theory to be considered a valid one for the observed baryon number asymmetry, it should not only satisfy the Sakharov conditions, but also predict a value of η which is close to experimental observations.

3.2 Baryogenesis from the Electroweak phase transition

Given the Sakharov conditions that we outlined in Section 3.1, we need to show that the Standard Model, along with the mechanism of electroweak phase transition, do indeed provide a model for baryon number asymmetry. We will discuss the the second Sakharov condition first, because CP violation in the Standard Model has been seen experimentally, and is therefore well-established. This CP violation was first observed through K_0-$\bar{K}_0$ mixing. The violation is caused essentially by the fact that the weak flavor eigenstates are not the mass eigenstates for quarks. As a result there exists a unitary matrix, known as the CKM matrix, which allows one to switch from the flavor basis to the mass basis. Kobayashi and Masakawa (KM of CKM) famously showed that for three generations of fundamental particles, there exists one non-zero phase δ in the matrix which leads to CP violation of the theory. This CP violation seems to satisfy the second of Sakharov's criteria. However, it should be noted that the latest measurements of δ yield a value which is considered to be too small to account for all the observed baryon number asymmetry by itself. It seems that one needs to go beyond the Standard Model to introduce new CP violating terms, which do not interfere with other measurements, but are large enough to cause the baryon asymmetry.

Next we look at Sakharov's first criterion - that of processes within the theory that can lead to baryon number asymmetries. We know that at low energies, and even at energies probed at colliders today, lepton number and baryon number are conserved. So, at first glance, it seems as if the Standard Model does not describe any process in which baryon number is violated. However, it turns out that the above statements are true only perturbatively, and there exist non-perturbative processes which do violate baryon number with in the Standard Model. These processes, involving instantons, are not important at energy scales which are accessible to us, but are very important in the early universe, where temperatures and densities were very high. To understand the origin of these processes, we have to remember that chiral symmetry is broken at the quantum level, leading to the ABJ anomaly. This means that even though the currents corresponding to baryon number and lepton number are conserved at the classical level, they are not conserved at the quantum level. The equation for the currents then becomes

$$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = \frac{n_F}{32\pi^2}\left(g^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right) , \tag{6}$$

where n_F counts the number of families in the Standard Model. $\tilde{W}^{a\mu\nu} = (1/2)\epsilon^{\mu\nu\alpha\beta}W^a_{\alpha\beta}$ is the dual of the field strength tensor of the $SU(2)_L$ field. The dual of the $U(1)_Y$ field strength tensor is similarly defined to be $\tilde{B}^{\mu\nu}$. This immediately tells us that $J^B_\mu - J^L_\mu$ is conserved at the quantum level. At the quantum level, then, the conserved quantity is $B - L$, and not B or L individually.

One can write the RHS of Eq. (6) as a total divergence so that

$$\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = n_F \partial_\mu (K^\mu + k^\mu) , \tag{7}$$

where

$$K^\mu = \frac{g^2}{32\pi^2}\epsilon^{\mu\nu\alpha\beta}\left(W^a_{\nu\alpha}W^a_\beta - \frac{1}{3}g\epsilon_{abc}W^a_\nu W^b_\alpha W^c_\beta\right) , \tag{8}$$

$$k^\mu = -\frac{g'^2}{32\pi^2}\epsilon^{\mu\nu\alpha\beta}B_{\nu\alpha}B_\beta . \tag{9}$$

Since K^μ is not gauge invariant, the integral over all space with vanishing boundary conditions does not necessarily yield 0 as the result. However, it does hold true for k^μ. Using this fact, we can write down the change in the baryon number between an initial time t_i and a final time t_f as

$$\Delta B = n_F(N_{CS}(t_f) - N_{CS}(t_i)) = \Delta N_{CS} \ , \tag{10}$$

where

$$N_{CS} = \frac{g^2}{32\pi^2} \int d^3x \epsilon^{ijk} \left(W_{ij}^a W_k^a - \frac{1}{3} g \epsilon_{abc} W_i^a W_j^b W_k^c \right) \ . \tag{11}$$

N_{CS} is known as the Chern-Simons number. As pointed out before this is not a gauge invariant number, though ΔN_{CS} is gauge invariant. We can see from the definition of the Chern-Simons number that it is not a local quantity and is a topological charge, different values for which characterize different vacuua. The baryon number violating processes are those which change the Chern-Simons number by an integer. Since we have linked baryon number violating processes to a change in a topological quantity, we can now understand why these processes do not take place at low energies, and why they do not show up in perturbative expansions.

The different vacuua, which are the minima of some complicated gauge potential, will be separated by energy barriers. The solution which gives the profile of the potential with the lowest energy barriers between successive vacuua is known as the *sphaleron* solution, and is used to calculate the tunnel probabilities between adjacent minima. This specific tunneling process would then give rise to a situation where the baryon number is violated by 9 (3 generations and 3 colors per generation) and the lepton number is violated by 3 (3 generations). To estimate the rates of tunneling, and hence the rates of baryon number violating processes, one has to know the height of the sphaleron barrier. This value was found to be

$$E_{sph} = \frac{2M_W}{\alpha_W} B \left(\frac{\lambda}{g^2} \right) \ , \tag{12}$$

where $\alpha_W = g^2/4\pi$ and B is a constant lying between 1.5 and 2.7 depending upon the value of λ which measures the Higgs self-coupling. M_W is the temperatures dependent mass of the W-boson. The rate per unit volume of baryon number violating processes in the phase where electroweak symmetry is broken was calculated to be

$$\frac{\Gamma^{sph}}{V} = \kappa_1 \left(\frac{M_W}{\alpha_W T} \right)^3 M_W^4 e^{-E_{sph}(T)/T} \ , \tag{13}$$

where κ_1 is some numerical constant.

In the unbroken phase, there exist no exact calculations to predict this rate. However, by dimensional analysis and numerical simulations, the rate is expected to be

$$\frac{\Gamma^{sph}}{V} = \kappa_2(\alpha_W T)^4 \; . \tag{14}$$

κ_2 is some other numerical constant. As expected, the Boltzmann factor is absent in the unbroken phase, where temperatures are greater than the sphaleron barrier. At these high temperatures, the rates of these processes would be significant.

Now that we have seen the existence of baryon number violating processes within the Standard Model, we need to see how electroweak symmetry breaking allows us to satisfy the third and final Sakharov condition - that of interactions taking place outside thermal equilibrium. First of all, we need to understand why a phase transition is needed for the universe to go out of equilibrium. As the Universe cooled and expanded, the rate of expansion of the universe slowed. The measure of the rate of expansion of the universe is the Hubble's constant, H. One can work out what the rate of expansion at a time just before the the electroweak symmetry was broken and the Higgs field acquired its vev. One can also calculate the rate of baryon number violating processes at the same temperature. As we have seen, in the unbroken phase, these rates are high as they are not suppressed by a Boltzmann factor, and go as the fourth power of the temperature. The Hubble constant on the other hand depends quadratically on the temperature. At high temperatures near the Big Bang, we would expect $\Gamma^{sph} >> H$. This means that there are too many interactions for the expansion of the universe to take the system out equilibrium. We need another mechanism which can do this, and the electroweak phase transition seems to provide one such mechanism.

For the electroweak phase transition, we have already seen that the vacuum expectation value of the Higgs field can be considered as the order parameter. It goes from 0 in the symmetric phase to some finite value in the broken phase. As can be seen from Fig. (1), if the phase transition is first order, the change in the vev is discontinuous, and the two minima are separated by an energy barrier. On the other hand, if the transition is second order, the vev changes continuously as we go from above T_c to below T_c, and there is no energy barrier in this case. The energy barrier will turn out to be crucial in our arguments, and is the reason why the electroweak phase transition needs to be discontinuous if it is to successfully explain baryogenesis.

As the universe cools to below the critical temperature at which the phase transition takes place, bubbles of the true vacuum, which is the broken phase, starts forming within the sea of the false vacuum, the unbroken phase. The false vacuum continues to exist below T_c as the transition is first order, just

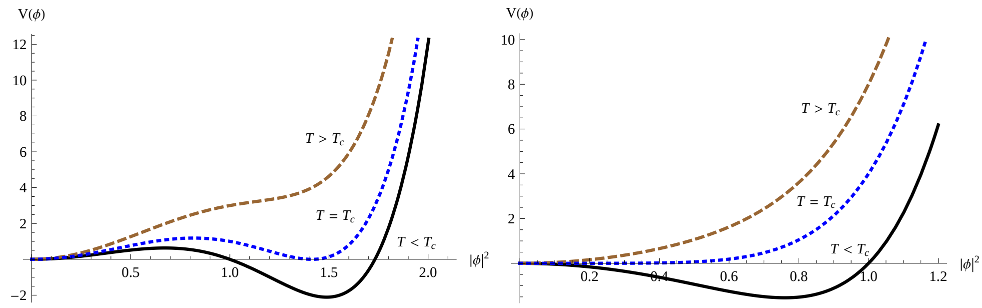

Figure 1: The profile of the potential $V(\phi)$ for a first order transition on the left, and for second order transition on the right for various temperatures above and below T_c. Note that the the position of the minima changes abruptly at T_c for a first order transition (left panel) and continuously for a second order one (right panel).

like supercooling in a liquid-vapor transition. Initially the bubbles are small, and the reduction in the free energy from the bulk term is too small to compete against the surface tension. However, as the temperature falls, the bubbles become larger, and they can overcome the surface tension effects and start growing. Eventually, these bubbles of the true vacuum nucleate and fill up the entire universe. As these bubbles grow and nucleate, different regions of the universe pass through the phase boundary between the broken and the unbroken phase. The transition being discontinuous, the order parameter jumps rapidly across these boundaries. The other fields change rapidly as well. This is what drives the system away from equilibrium, as the baryon number violating processes are not fast enough to keep pace with this rapid change. We see that a first order electroweak phase transition is needed to drive the system away from equilibrium. For a second order phase transition, the change of the vev across boundaries is continuous, and therefore would leave the system in thermal equilibrium.

We have pointed out earlier in Eqs. (13) and (14) that the rates of baryon number violating processes are very different in the two phases. It is suppressed in the broken phase by a Boltzmann factor, which is not present in the expression for the rate in the unbroken phase. To achieve a non-zero value of η, we need a large number of baryon number violating processes in the unbroken phase, and very few such processes in the broken phase. This would mean that as different points in the universe move across the boundary, from the unbroken phase to the broken phase, the baryon number asymmetry would get frozen. For it to remain frozen, one requires the rate to fall drastically at that temperature. Using Eq. (12) in Eq. (13), along with the fact that $M_W \propto g v_T$, we get

$$\Gamma^{sph} \propto e^{-4\pi B v_T / gT} \ . \tag{15}$$

All other parameters being fixed, this leads us to the conclusion that for the baryon number anomaly to get frozen in the broken phase, we should have

$$\frac{V_{Tc}}{T_c} \gtrsim 1 \ , \tag{16}$$

which is the condition for a strong first order transition.

We have seen in this section how the Standard Model along with the Higgs mechanism is able to satisfy all of Sakharov's criteria, and therefore be a viable model for explaining the baryon number asymmetry in the universe. We have also seen that in order to so, we need the phase transition to be strongly first order.

4 Summary and Discussion

In this paper, we saw how symmetry breaking and phase transitions are essential ingredients of the Standard Model via the Higgs mechanism. These ideas could also be used to explain the baryon number asymmetry that we observe in the universe. In Section 2, we saw how this mechanism provides fermions and gauge bosons with masses, which would otherwise have been forbidden by symmetry. In section 3, we looked at the conditions which a theory of baryogenesis must satisfy. While looking for processes within the Standard Model which satisfy this criteria, we saw an interesting non-perturbative way in which baryon number violating processes occur within the Standard Model: by changing the Chern-Simons number, which is a topological charge associated with the gauge configuration of the $SU(2)_L$ field. Later, we saw that if we are to explain baryogenesis through this phase transition, there is a constraint on the nature of the phase transition - a strongly first order phase transition is required.

Though electroweak symmetry breaking offers an elegant solution to the problem of baryogenesis, the jury is still out as to whether it can work without any modifications to the Standard Model. We have already pointed out that the only source of CP violation in the Standard Model is the parameter δ in the CKM matrix. The current bounds on its value from experiments seem to suggest that it is too small to produce the large baryon number asymmetry. Another issue with electroweak baryogenesis is that, according to current understanding, if the phase transition indeed has to be first order, it is commensurate with a Higgs mass which falls in a region which has been ruled out by experiments. However, this may not be correct if one takes into account higher order loop corrections to the Higgs potential, and is an open question.

These problems have led people to look at other models for baryogenesis. Almost all of them require extensions of the Standard Model to include new particles or symmetries. For example, the models based on Grand Unified Theories requires one to embed the Standard Model in a higher symmetry group. Other models based on supersymmetry require the existence of supersymmetric counterparts of all knows bosons and fermions. There are also models which are based on baryogenesis via leptogenesis, and these require the existence of Majorana fermions. Given current experimental data, it is not possible to determine which of these theories can be rejected. Hence this is an open field, where active research is underway, both in terms of experiments, as well as theoretical models.

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