Status of the Electroweak Baryogenesis

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1 Introduction

The origin of the matter in the Universe has been an important issue in particle physics and astrophysics. The baryon asymmetry of the universe (BAU) is measured by the ratio of baryon number density and entropy density n_B/s, which must be $(0.37-0.88)\times 10^{-10}$ for successful nucleosynthesis. In order to produce this BAU, the model of particle physics must satisfy the three conditions proposed by Sakharov[1], and several scenarios satisfying them have been considered. Among them, the GUT-baryogenesis is the first that is based on a field-theoretical model[2]. After that, the anomalous $(B+L)$-nonconservation induced by the chiral anomaly in the electroweak theory was found not to be suppressed at high temperatures. In the broken phase of the electroweak gauge symmetry, the $(B+L)$-changing rate is governed by the classical saddle-point configuration called "sphaleron" at finite temperatures. Even in the symmetric phase, where there is no sphaleron solution, we refer to the $(B+L)$-changing process as sphaleron process.

The discovery of the sphaleron opened new possibilities of baryogenesis. Once the universe experiences chemical equilibrium of the $(B+L)$-changing processes, the remnant B and L are proportional to the primordial $B-L$. This implies that nonzero lepton number L, which may be produced by the L-violating decay of heavy neutrinos, is converted to $B=-L$ in the period of sphaleron equilibrium. The idea of electroweak baryogenesis is to produce $B+L$ just before the sphaleron process decouples when nonequilibrium state is realized by the first-order electroweak phase transition (EWPT). It is an fascinating scenario in that it is based on physics which can be tested in near future. In my talk, I review the scenario of electroweak baryogenesis, focusing on the sphaleron process and constraints obtained by requiring that the baryon number is left over. Since I could not present all the equations and figures in the talk within this brief report, please refer to the file placed on the web page

`http://dirac.phys.saga-u.ac.jp/~funakubo/yitp/`

For more detail on the electroweak baryogenesis, see the review articles on this subject[3].

2 Sphaleron process

In any electroweak theory whose quark and lepton contents are the same as the minimal standard model (MSM), there hold the anomalous WT identities

$$\partial_\mu j^\mu_{B+L} = \frac{N_f}{16\pi^2}\left[g_2^2 \mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right], \qquad \partial_\mu j^\mu_{B-L} = 0, \tag{1}$$

where the tilde on the field strength denotes the Hodge dual of it and N_f is the number of fermion generations. Here $F_{\mu\nu}$ ($B_{\mu\nu}$) and g_2 (g_1) are the field strength tensor and the coupling constant of the $SU(2)_L$ ($U(1)_Y$) gauge field A_μ (B_μ), respectively. Combining these equations, we find that the change of baryon number can be expressed as

$$B(t_f) - B(t_i) = N_f\left[N_{CS}(t_f) - N_{CS}(t_i)\right] \tag{2}$$

where N_{CS} is the Chern-Simons number defined by

$$N_{CS}(t) = \int d^3\boldsymbol{x}\,\epsilon_{ijk}\left[g_2^2\mathrm{Tr}\left(F_{ij}A_k - \frac{2}{3}g_2A_iA_jA_j\right) - g_1^2B_{ij}B_k\right]_t \tag{3}$$

In the classical vacuum of the gauge field sector, $F_{\mu\nu} = B_{\mu\nu} = 0$, the gauge fields are expressed by pure gauge functions. $F = iU^{-1}dU$ and $B = dv$. As for $SU(2)$ gauge field, the unitary function $U(\boldsymbol{x})$, which is a map from $\boldsymbol{x} \in S^3$ to $U \in SU(2) \simeq S^3$, is classified by an integer N_{CS}. Hence the classical energy of the gauge sector has infinitely degenerate minima, which are labeled by N_{CS}. The anomalous WT identity implies that when the background changes with $\Delta N_{CS} = 1$, B and L changes by unity in each generation. The transition rate with $\Delta N_{CS} = 1$ at zero temperature is determined by the instanton action, which is so large for the weak theory that the rate is negligibly small. After the discovery of the sphaleron configuration[4], the transition is suppressed by $e^{-E_{\mathrm{sph}}/T}$, where E_{sph} is the energy of the sphaleron solution[5]. This Boltzmann suppression persists up to the electroweak phase transition temperature T_C. At higher temperature than T_C, the rate per unit time is approximately given by $\alpha_W^4 T$. Comparing the time scales of the expansion of the universe $H(T)^{-1} \propto T^{-2}/M_{\mathrm{Pl}}$ and that of the sphaleron process, we find that the sphaleron process is in chemical equilibrium at T between $T_C \simeq 100$GeV and 10^{12}GeV.

In order to have nonzero BAU at present,

(i) $B - L$ must be produced before the sphaleron process decouples, or

(ii) $B + L$ is produced at the EWPT and the sphaleron process decouples just after that.

The latter standpoint is that of the electroweak baryogenesis. Simultaneous equilibrium of the sphaleron process and another L- or B-violating process immediately leads to the complete washout of any B and L. For example, the L-violating process in the see-saw model must decouple before the universe cooled down to 10^{12}GeV. This impose an lower bound on the heavy neutrino, so that an upper bound on the light neutrino[6]. An implication in another L-violating model was reported by Hasegawa[7].

3 Electroweak baryogenesis

For successful electroweak baryogenesis, nonequilibrium state must be realized by the first-order EWPT and sufficient CP violation in addition to the KM phase is necessary. In order for the sphaleron process to decouple just after the transition, the sphaleron rate must become smaller than the Hubble parameter at the transition temperature. This, in turn, requires that the expectation value of the Higgs field v_C at the transition must be larger than the temperature T_C: $v_C/T_C > 1$. In the MSM, this condition is converted to the upper bound on the Higgs mass. By a naive perturbative approximation of the finite-temperature effective potential, one can see that the bound is given by $m_h < 46$GeV, while more reliable lattice MC studies place $m_h < 65\mathrm{GeV}$. Any way, the MSM cannot satisfy this requirement of sphaleron decoupling. The high-temperature expansion of the effective potential suggests that the bosons with $m^2(v) \sim v^2$ enhance the v^3-terms, which makes the EWPT stronger. Therefore, one needs extensions of the MSM, which include more scalars such as the minimal supersymmetric standard model (MSSM), the two-Higgs-doublet model (2HDM) and so on. Among such extensions, the supersymmetric models are well motivated ones. Such models also have many sources of CP violation, such as the complex μ-parameter, A-terms, gaugino masses and the relative phase of the Higgs fields.

The study of phase transitions in models with several scalars is complicated, since the space of the order parameters has multidimensional structure. The 2HDM, including the MSSM, has three order parameters $(v_1, v_2, v_3) = (v_d, v_u \cos\theta, v_u \sin\theta)$, where v_3 is the CP-odd order parameter. The EWPT in the MSSM proceeds along almost constant $\beta = \tan^{-1}(v_u/v_d)$ and becomes strongly first order, if the lightest mass eigenstate of the stops is lighter than the top quark[9]. However, the constraint on the upper bound on the lightest Higgs boson still exists, which is predicted to be about 110GeV. This bound will be shifted to 120GeV, if one allow negative $m^2_{\tilde{t}_R}$, which is the soft mass of the singlet stop. We also studied the effects of CP violation in the squark sector on the EWPT in the MSSM, which is parameterized by $\mathrm{Im}(\mu A_t)$. Such CP violation will play an important role in generating the chiral charge flux, which triggers the nonequilibrium generation of $B + L$ in the symmetric phase region. It also induces the mixing among the scalar and pseudoscalar components of the Higgs bosons. In some cases, such a mixing makes a lightest Higgs boson lighter than 114GeV with very small VVH-coupling, which can escape from the LEP2 bound[10]. We showed that the CP violation weakens the strength of the EWPT, when $m_{H_1} \leq 110\mathrm{GeV}$[11]. Recalling the allowed region in the $(m_h, \tan\beta)$-space of the MSSM, rather narrow range of the parameters is left for the baryogenesis.

4 Summary

We showed that the mass of the (lightest) Higgs boson in the MSM and MSSM is bounded from above, if we require the EWPT to be so strongly first order that the sphaleron process decouples just after it. This bound excludes the MSM as a viable model for electroweak baryogenesis. If the lightest Higgs in the MSSM is heavier than 110GeV, the EWPT will be too weak even with a light stop. This bound may be extended to 120GeV, when we admit negative soft mass-squared of the singlet stop. If the lightest Higgs is heavier than 135GeV, the MSSM is not a correct model to describe the Higgs sector.

Then the Next-to-MSSM, which contains a gauge-singlet superfield in addition to the MSSM, may be the next candidate sharing merits of the MSSM. It has been long believed that it predicts strongly first-order EWPT because of the scalar cubic terms in the tree-level potential. We recently found that it allows several phases at finite temperatures and has four kinds of phase transitions, one of which is strongly first order without a light stop[12]. Another well-studied extension is the 2HDM, for which the lightest Higgs boson can be as heavy as 130GeV while the EWPT is strongly first order. Such a situation is possible when the scalar self-coupling λ is large. Then the corrections to the vertices of the Higgs boson are expected to be so large that the deviation from the MSM will be observed[13].

Here we concentrated on the relation between the Higgs mass and the EWPT. As for quantitative evaluation of the generated BAU at the phase transition in the extended models, refer to the review articles and references therein[3].

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