

DESY-07-186  
October 2007

# Baryogenesis – 40 Years Later<sup>1</sup>

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**Abstract.** The classical picture of GUT baryogenesis has been strongly modified by theoretical progress concerning two nonperturbative features of the standard model: the phase diagram of the electroweak theory, and baryon and lepton number changing sphaleron processes in the high-temperature symmetric phase of the standard model. We briefly review three viable models, electroweak baryogenesis, the Affleck-Dine mechanism and leptogenesis and discuss the prospects to falsify them. All models are closely tied to the nature of dark matter, especially in supersymmetric theories. In the near future results from LHC and gamma-ray astronomy will shed new light on the origin of the matter-antimatter asymmetry of the universe.

**Keywords:** Baryogenesis, Leptogenesis, Dark Matter

**PACS:** 98.80.Cq,95.35.+d,12.60.Jv,95.30.Cq

## MATTER-ANTIMATTER ASYMMETRY

The cosmological matter-antimatter asymmetry can be dynamically generated if the particle interactions and the cosmological evolution satisfy Sakharov's conditions [1],

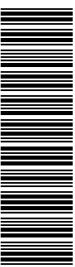
- baryon number violation,
- $C$  and  $CP$  violation,
- deviation from thermal equilibrium.

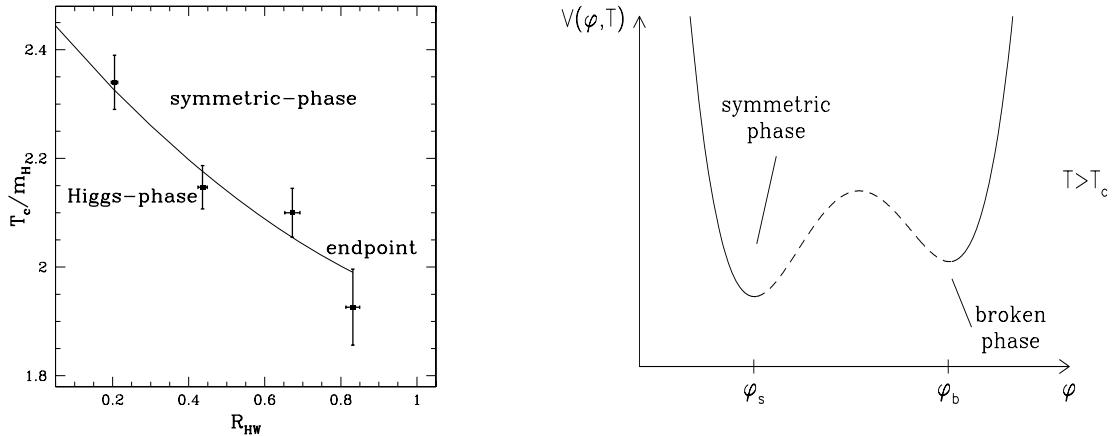
Although the baryon asymmetry is just a single number, it provides an important connection between particle physics and cosmology. In his seminal paper, 40 years ago, Sakharov not only stated the necessary conditions for baryogenesis, he also proposed a specific model. The origin of the baryon asymmetry were  $CP$  violating decays of super-heavy ‘maximons’ with mass  $\mathcal{O}(M_P)$  at an initial temperature  $T_i \sim M_P$ . The  $CP$  violation in maximon decays was related to the  $CP$  violation observed in  $K^0$ -decays, and the violation of baryon number led to a proton lifetime  $\tau_p > 10^{50}$  years, much larger than current estimates in grand unified theories.

At present there exist a number of viable scenarios for baryogenesis. They can be classified according to the different ways in which Sakharov's conditions are realized. In grand unified theories baryon number ( $B$ ) and lepton number ( $L$ ) are broken by the interactions of gauge bosons and leptoquarks. This is the basis of classical GUT baryogenesis (cf. [2]). In a similar way, lepton number violating decays of heavy Majorana neutrinos lead to leptogenesis [3]. In the simplest version of leptogenesis the initial abundance of the heavy neutrinos is generated by thermal processes. Alternatively, heavy neutrinos

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<sup>1</sup> 13th International Symposium on Particles, Strings and Cosmology, Imperial College London, July 2007





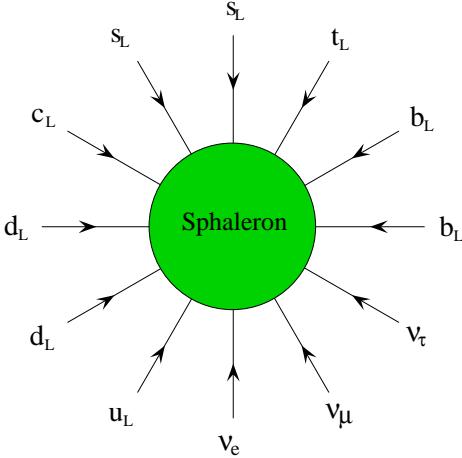
**FIGURE 1.** *Left:* Critical temperature  $T_c$  of the electroweak transition as function of  $R_{HW} = m_H/m_W$ ; from [6]. *Right:* Effective potential of the Higgs field  $\varphi$  at temperature  $T > T_c$ .

may be produced in inflaton decays or in the reheating process after inflation. Because in the standard model baryon number,  $C$  and  $CP$  are not conserved, in principle the cosmological baryon asymmetry can also be generated at the electroweak phase transition [4]. A further mechanism of baryogenesis can work in supersymmetric theories where the scalar potential has approximately flat directions. Coherent oscillations of scalar fields can then generate large asymmetries [5].

The theory of baryogenesis crucially depends on nonperturbative properties of the standard model, first of all the nature of the electroweak transition. A first-order phase transition yields a departure from thermal equilibrium. Fig. 1 shows the phase diagram of the electroweak theory, i.e. the critical temperature in units of the Higgs mass,  $T_c/m_H$ , as function of the Higgs mass in units of the W-boson mass,  $R_{HW} = m_H/m_W$  [6, 7]. For small Higgs masses the phase transition is first-order; above a critical Higgs mass,  $m_H > m_H^c \simeq 72$  GeV, it turns into a smooth crossover [8, 9]. This upper bound for a first-order transition has to be compared with the lower bound from LEP,  $m_H > 114$  GeV. Hence, there is no departure from thermal equilibrium at the electroweak transition in the standard model.

The second crucial nonperturbative aspect of baryogenesis is the connection between baryon number and lepton number in the high-temperature, symmetric phase of the standard model. Due to the chiral nature of the weak interactions  $B$  and  $L$  are not conserved [10]. At zero temperature this has no observable effect due to the smallness of the weak coupling. However, as the temperature reaches the critical temperature  $T_c$  of the electroweak phase transition,  $B$  and  $L$  violating processes come into thermal equilibrium [4]. The rate of these processes is related to the free energy of sphaleron-type field configurations which carry topological charge. In the standard model they lead to an effective interaction of all left-handed fermions [10] (cf. Fig. 2),

$$O_{B+L} = \prod_i (q_L q_L q_L q_L l_L) , \quad (1)$$



**FIGURE 2.** One of the 12-fermion processes which are in thermal equilibrium in the high-temperature phase of the standard model.

which violates baryon and lepton number by three units,

$$\Delta B = \Delta L = 3 . \quad (2)$$

The sphaleron transition rate in the symmetric high-temperature phase has been evaluated by combining an analytical resummation with numerical lattice techniques [11]. The result is, in accord with previous estimates, that  $B$  and  $L$  violating processes are in thermal equilibrium for temperatures in the range

$$T_{EW} \sim 100 \text{ GeV} < T < T_{SPH} \sim 10^{12} \text{ GeV} . \quad (3)$$

Sphaleron processes have a profound effect on the generation of the cosmological baryon asymmetry. An analysis of the chemical potentials of all particle species in the high-temperature phase yields the following relation between the baryon asymmetry and the corresponding  $L$  and  $B - L$  asymmetries,

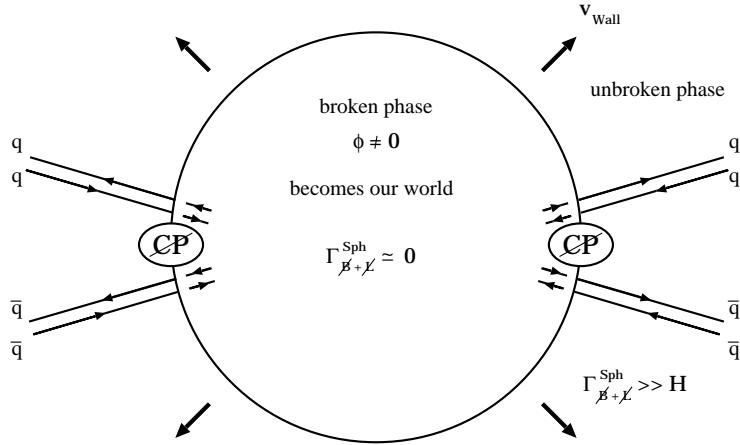
$$\langle B \rangle_T = c_S \langle B - L \rangle_T = \frac{c_S}{c_S - 1} \langle L \rangle_T . \quad (4)$$

Here  $c_S$  is a number  $\mathcal{O}(1)$ . In the standard model with three generations and one Higgs doublet one has  $c_S = 28/79$ .

We conclude that lepton number violation is necessary in order to generate a cosmological baryon asymmetry<sup>2</sup>. However, it can only be weak, because otherwise any baryon asymmetry would be washed out. The interplay of these conflicting conditions leads to important constraints on neutrino properties and on possible extensions of the standard model in general.

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<sup>2</sup> In the case of Dirac neutrinos, which have extremely small Yukawa couplings, one can construct leptogenesis models where an asymmetry of lepton doublets is accompanied by an asymmetry of right-handed neutrinos such that the total lepton number is conserved and  $\langle B - L \rangle_T = 0$  [12].

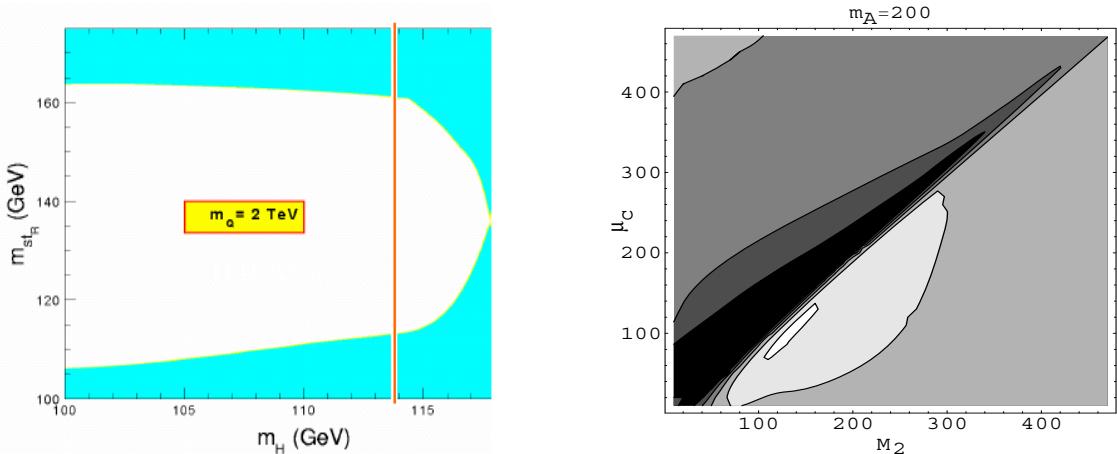


**FIGURE 3.** Sketch of nonlocal electroweak baryogenesis. From [13].

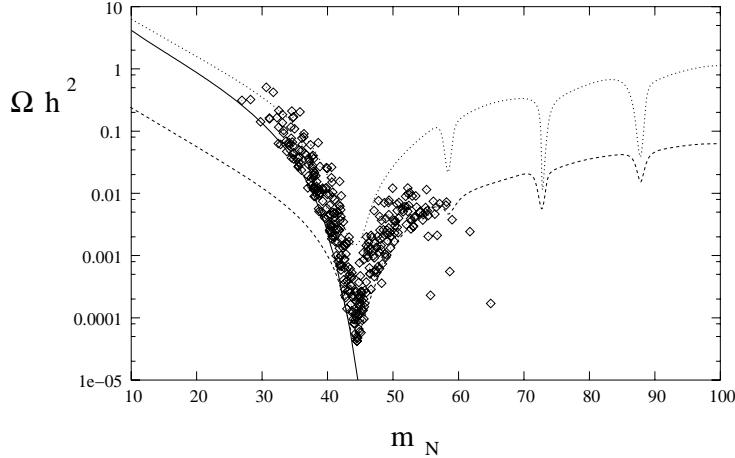
## ELECTROWEAK BARYOGENESIS

A first-order electroweak phase transition proceeds via nucleation and growth of bubbles (cf. [13, 14]). This can provide the departure from thermal equilibrium, which is necessary for electroweak baryogenesis. *CP* violating reflections and transmissions at the bubble surface then generate an asymmetry in baryon number, and for a sufficiently strong phase transition this asymmetry is frozen in the true vacuum inside the bubble (cf. Fig. 3).

As discussed in the previous section, in the standard model the electroweak transition is just a smooth crossover. Hence, there is no departure from thermal equilibrium and baryogenesis cannot take place. The situation changes in two-Higgs doublet models (cf. [14, 15]) and in supersymmetric extensions of the standard model where one can



**FIGURE 4.** *Left:* Upper and lower bounds on the scalar top mass  $m_{st_R}$  as function of the Higgs mass  $m_H$ . From [16]. *Right:* In the black area of the  $(\mu_c, M_2)$  plane of  $\mu$ -parameter and gaugino mass electroweak baryogenesis is viable. From [17].



**FIGURE 5.** Neutralino relic density as function of the neutralino mass in the nMSSM for different parameter sets of the model (scattered points). From [18].

have a sufficiently strong first-order phase transition (cf. [14]). This requires, however, a rather exceptional mass spectrum of superparticles. As the left panel of Fig. 4 shows, one scalar top-quark has to be lighter than the top-quark whereas other scalar quarks are 2 TeV heavy. Also gaugino masses have to be rather small (cf. Fig. 4, right panel).

Even more stringent constraints are obtained if the lightest neutralino is required to be the dominant component of cold dark matter. This case has been studied in detail for the nMSSM, a minimal extension of the MSSM with a singlet field [18]. Fig. 5 shows the neutralino relic density as function of the neutralino mass for various parameter sets of the model represented by the scattered points. It is remarkable that the neutralino has to be very light. This suggests that, should supersymmetry be discovered at the LHC, the consistency of WIMP dark matter and electroweak baryogenesis will be a highly non-trivial test of supersymmetric extensions of the standard model.

## AFFLECK-DINE BARYOGENESIS

In general the scalar potential of supersymmetric theories has many flat directions involving scalar fields which carry baryon or lepton number. Typical examples in the MSSM are

$$(LH_u), \quad (U^c D^c D^c), \quad (5)$$

where  $L$ ,  $H_u$ ,  $U^c$  and  $D^c$  denote lepton doublets, one of the Higgs doublets and quark fields, respectively. During inflation these fields generically develop large vacuum expectation values. After inflation these condensates lead to coherent oscillations, which can store large baryon and lepton charge densities. The decay of these condensates eventually converts the scalar charge densities to ordinary fermionic baryon and lepton number.

This ‘AD mechanism’ is a prominent example of nonthermal baryogenesis. So far no ‘standard model’ of AD baryogenesis has emerged, and it appears difficult to falsify this