Overview of Electroweak Baryogenesis

C. Balázs[1], M. Carena[2], A. Menon[1,3], D.E. Morrissey[4], and C.E.M. Wagner[1,3]
[1] HEP Division, Argonne National Laboratory, 9700 Cass Ave., Argonne, IL 60439, USA
[2] Fermi National Accelerator Laboratory, P.O.Box 500, Batavia, IL 60510, USA
[3] Enrico Fermi Institute, Univ. of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA and
[4] Department of Physics, University of Michigan, 3444B Randall Lab., Ann Arbor, MI 48109, USA

This review highlights the essentials and the consequences of the electroweak baryogenesis mechanism in the minimal supersymmetric extension of the standard model.

Recent improvements of the astrophysical and cosmological data, most notably due to the Wilkinson Microwave Anisotropy Probe (WMAP) [1], have determined the baryon density of the Universe to be

$$\Omega_B h^2 = 0.0224 \pm 0.0009, \tag{1}$$

with $h = 0.71^{+0.04}_{-0.03}$. According to the observations, the baryon density is dominated by baryons while anti-baryons are only products of high energy processes. The source of this baryon–anti-baryon asymmetry is one of the major puzzles of particle physics and cosmology.

Assuming that inflation washes out any initial baryon asymmetry after the Big Bang, there should be a dynamic mechanism to generate the asymmetry after inflation. Any microscopic mechanism for baryogenesis must fulfill the three Sakharov requirements [2]:

- baryon number (B) violation,
- CP violation, and
- departure from equilibrium (unless CPT is violated [3]).

All three requirements are satisfied in both the standard model (SM) and its minimal supersymmetric extension (MSSM) during the electroweak phase transition, and this is the basis for electroweak baryogenesis (EWBG) [4–8]. While electroweak baryogenesis is viable in the MSSM, SM processes cannot generate a large enough baryon asymmetry during the electroweak phase transition.

Baryon number violation occurs in the SM and the MSSM due to anomalous sphaleron transitions that violate $(B+L)$ [9]. These transitions are exponentially suppressed at low temperatures in the electroweak broken phase [10, 11], but become active at high temperatures when the electroweak symmetry is restored [12–16]. In the absence of other charge asymmetries, like $(B-L)$, they produce baryons and anti-baryons such that the net baryon number relaxes to zero, and so do not by themselves generate a baryon asymmetry [17].

If the electroweak phase transition is first order, bubbles of broken phase nucleate within the symmetric phase as the Universe cools below the critical temperature. These provide the necessary departure from equilibrium. EWBG then proceeds as follows [18]. CP violating interactions in the bubble walls generate chiral charge asymmetries which diffuse into the symmetric phase in front of the walls. There, sphaleron transitions, which are active in the symmetric phase, convert these asymmetries into a net baryon number. This baryon number then diffuses into the bubbles where the electroweak symmetry is broken. The chiral charges produced in the bubble wall are able to diffuse into the symmetric phase, where they are approximately conserved, but not into the broken phase, where they are not.

Sphaleron transitions within the broken phase tend to destroy the baryon number generated outside the bubble. To avoid this, the sphaleron transitions within the broken phase must be strongly suppressed. This is the case provided the electroweak phase transition is *strongly* first order [19],

$$v(T_c)/T_c \gtrsim 1, \tag{2}$$

where $v(T_c)$ denotes the Higgs vacuum expectation value at the critical temperature T_c.

The strength of the electroweak phase transition may be determined by examining the finite temperature effective Higgs boson potential. The Higgs vacuum expectation value at the critical temperature is inversely proportional to the Higgs quartic coupling, related to the Higgs mass. For sufficiently light Higgs bosons, a first-order phase transition can be induced by the loop effects of light bosonic particles, with masses of order the weak scale and large couplings to the Higgs fields. The only such particles in the SM are the gauge bosons, and their couplings are not strong enough to induce a first-order phase transition for a Higgs mass above the LEP II bound [20–22].

Within the MSSM, there are additional bosonic degrees of freedom which can make the phase transition more strongly first-order. The most important contribution comes from a light stop, which interacts with the Higgs field with a coupling equal to the top-quark Yukawa. In addition, a light stop has six degrees of freedom, three of colour and two of charge, which further enhances the effect on the Higgs potential. Detailed calculations show that for the mechanism of electroweak baryogenesis to work, the lightest stop mass must be less than the top mass but greater than about 120 GeV to avoid colour-breaking minima. Simultaneously, the Higgs boson involved in breaking the electroweak symmetry must be lighter than 120 GeV [23–34], only slightly above the present experimental bound [35],

$$m_h \gtrsim 114 \text{ GeV}, \tag{3}$$

which is valid for a Higgs boson with SM-like couplings to the gauge bosons.

The combined requirements of a first-order electroweak phase transition, strong enough for EWBG, and a Higgs boson mass above the experimental limit severely restrict the allowed values of the stop parameters. To avoid generating too large a contribution to $\Delta\rho$, the light stop must be mostly right-handed. Since the stops generate the most important radiative contribution to the Higgs boson mass in the MSSM [36], the other stop must be considerably heavier in order to raise the Higgs mass above the experimental bound, Eq. (3). For the stop soft supersymmetry-breaking masses, this implies [29]

$$\begin{aligned} m^2_{U_3} &\lesssim 0, \\ m^2_{Q_3} &\gtrsim (1 \text{ TeV})^2. \end{aligned} \tag{4}$$

A similar tension exists for the combination of soft SUSY breaking parameters defining the stop mixing, $X_t = |A_t - \mu^*/\tan\beta|/m_{Q_3}$, and $\tan\beta$. Large values of these quantities tend to increase the Higgs mass at the expense of weakening the phase transition or the amount of baryon number produced. The allowed ranges have been found to be [29]

$$\begin{aligned} 5 \lesssim \tan\beta \lesssim 10, \\ 0.3 \lesssim |A_t - \mu^*/\tan\beta|/m_{Q_3} \lesssim 0.5. \end{aligned} \tag{5}$$

A strong electroweak phase transition is only a necessary condition for successful EWBG. In addition, a CP violating source is needed to generate a chiral charge asymmetry in the bubble walls. Within the MSSM, the dominant source is produced by the charginos, and is proportional to $Im(\mu\, M_2)$ [37–40]. For this source to be significant, the charginos must be abundant in the plasma, which requires that they not be too much heavier than the temperature of the plasma, $T \sim T_c$. In the recent analysis of Ref. [40], the authors found the bounds

$$\begin{aligned} |Arg(\mu\, M_2)| &\gtrsim 0.1, \\ \mu, M_2 &\lesssim 500 \text{ GeV}. \end{aligned} \tag{6}$$

These conditions are very relevant to the issue of neutralino dark matter.

The need for a large CP violating phase, Eq. (6), implies that there is a danger of violating the experimental bounds on the electric dipole moments (EDM) of the electron, neutron, and ^{199}Hg atom since phases generate new contributions to these EDM's. The leading contributions arise at one loop order, and they all contain an intermediate first or second generation sfermion. They become negligible if these sfermions are very heavy, $m_{\tilde{f}} \gtrsim 10$ TeV. Such large masses have only a very small effect on EWBG. At two-loop order, if $Arg(\mu\, M_2) \neq 0$, there is a contribution involving an intermediate chargino and Higgs boson [41, 42]. Since EWBG requires that this phase be non-zero and that the charginos be fairly light, the two-loop contribution is unavoidable if EWBG is to be successful. Thus, EDM limits strongly constrain the EWBG mechanism in the MSSM. Similarly, the branching ratio for $b \to s\gamma$ decays is also sensitive to this phase, and therefore imposes a further constraint on the EWBG mechanism.

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