Matter - Antimatter Asymmetry of the Universe

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The observable universe exhibits an overwhelming dominance of matter over antimatter. Understanding the origin of this baryon asymmetry is one of the most profound questions in cosmology and particle physics. This report presents a detailed and comprehensive study of the theoretical foundations, observational constraints, and leading models that attempt to explain the generation of baryon asymmetry. We begin by reviewing the evidence for matter-antimatter asymmetry and describing Sakharov's three necessary conditions for baryogenesis. We then examine multiple baryogenesis scenarios, including Grand Unified Theory (GUT) baryogenesis, electroweak baryogenesis, Leptogenesis, and the Affleck-Dine mechanism. A comparative analysis highlights the strengths and limitations of each model in light of cosmological and experimental constraints.

1. INTRODUCTION

The puzzle of matter dominating over antimatter in the Universe has been one of the important questions in understanding the evolution of our Universe. Ideally, the Big Bang should have created equal amounts of both matter and antimatter in the early universe. But currently, we see everything from the tiniest life forms on Earth to largest stellar objects made almost entirely of matter. There are no signs of antimatter found.

Antimatter particles share the same mass ($m = \bar{m}$) and decay widths ($\Gamma = \bar{\Gamma}$) as their matter counterparts, but qualities such as electric charge ($Q = -\bar{Q}$) are opposite. The positively charged positron, for example, is the antiparticle to the negatively charged electron. The existence of antimatter is a direct consequence of combining two of the most fundamental concepts of physics, theory of relativity and quantum mechanics. Its theoretical prediction comes from these abstract principles [1] and their experimental discovery [2] is one the greatest achievements in physics.

The convenient dimensionless number which characterizes the magnitude of baryon asymmetry of the universe is the ratio of the baryonic charge density ($n_B - n_{\bar{B}}$) of the universe to the number density of the photons in the cosmic microwave background. Observational data (CMB) confirm that the ratio of baryons to photons is approximately [3]:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}. \tag{1}$$

where $n_\gamma = 411.4(T_\gamma/2.736)^3 cm^{-3}$ and $T_\gamma = 2.736$ K. Direct observations of baryonic matter in the universe give for β, roughly speaking, one third of the above number, in particular because a large amount of baryons may be invisible (the recent discovery by the Hubble Space Telescope of very faint galaxies gives a larger fraction of directly observed baryonic matter). A more accurate estimate can be obtained from primordial nucleosynthesis, from which the result 1 is inferred. A perfectly symmetric universe would have produced equal amounts of matter and antimatter during the big bang, leading to mutual annihilation and leaving behind a cold, dilute universe incompatible with galaxy formation or life. Thus, a dynamical mechanism to generate the asymmetry is essential.

Historically, the first systematic proposal was by Andrei Sakharov (1967) [4], who established that three conditions : baryon number violation, C and CP violation, and departure from thermal equilibrium must be satisfied for baryogenesis to occur. Over the decades, a wide variety of models have been developed and refined. This report presents a comprehensive review of these mechanisms and their implications. Firstly, we will look at evidence that tells us matter dominating over antimatter and then discuss the conditions required for this asymmetry.

2. OBSERVATIONAL EVIDENCE FOR MATTER-ANTIMATTER ASYMMETRY

2.1. Cosmic Microwave Background

High-precision measurements of the cosmic microwave background provide the strongest evidence for the baryon asymmetry. Acoustic peak structures in the CMB temperature and polarization spectra are directly sensitive to the baryon density. Measurements from WMAP and Planck reveal precise values for the baryon density parameter [3]:

$$\Omega_b h^2 \approx 0.022.$$

The tiny value implies that for every billion photons, there is roughly one excess baryon, meaning a massive annihilation of primordial matter–antimatter must have occurred, leaving behind only the small surplus that forms all visible matter. The baryon-to-photon ratio derived from acoustic peak analysis is consistent with Big Bang Nucleosynthesis predictions.

2.2. Big Bang Nucleosynthesis

Big Bang Nucleosynthesis provides an independent measurement of baryon number by predicting primordial abundances of light elements : Deuterium, Helium 3, Helium 4 , Lithium 7 as a function of η_B [5]. The theoretical predictions agree with observed abundances only if $\eta_B = (5-6) \times 10^{-10}$ which is consistent with the CMB value. We can conclude if significant regions of antimatter existed during BBN, annihilation at matter–antimatter boundaries would modify neutron-to-proton ratios and distort light-element abundances.

2.3. Absence of Gamma-Ray Signals from Matter–Antimatter Annihilation

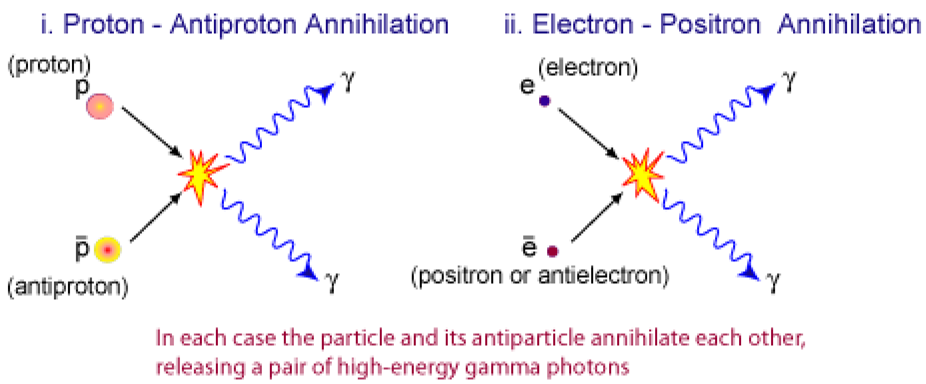

FIG. 1: Matter-Antimatter annihilation

If large antimatter domains existed near our galaxy or within the visible Universe, annihilation at their boundaries with matter domains would produce intense gamma-ray emission around the characteristic 100 MeV scale (from $\pi^0 \to 2\gamma$). However, no diffuse γ-ray background consistent with such annihilation is observed [6]. Fermi-LAT places extremely strong limits on annihilation signatures. any antimatter domains must be separated from us by at least gigaparsec scales, otherwise we would see unavoidable annihilation flux.

If antimatter stars or galaxies existed, they would eject anti-nuclei into space. Decades of cosmic-ray experiments (BESS, PAMELA, AMS-02) have found no confirmed anti-helium or heavier anti-nuclei. Even a single anti-helium candidate would profoundly challenge current models. Thus, there is no astrophysical evidence of macroscopic antimatter objects.

3. SAKHAROV CONDITIONS FOR BARYOGENESIS

Baryogenesis is the physical process that is hypothesized to have taken place during the early universe to produce baryonic asymmetry, the observation that only matter (baryons) and not antimatter (antibaryons) is detected in universe other than in cosmic ray collisions. A. Sakharov suggested that the baryon density might not represent some sort of initial condition, but might be understandable in terms of micro-physical laws [4]. These are stated as below :

3.1. Baryon Number Violating Processes

Let us first remember that the baryon number is defined as

$$B = \frac{1}{3}(n_q - n_{\bar{q}}), \tag{2}$$

where n_q and $n_{\bar{q}}$ are the number of quarks and anti-quarks. It seems obvious that, if $B = 0$ after inflation and all processes conserve B, we would never create the baryon asymmetry. So, we need processes such as $X \to Y + b$, where $B_b = 1$, $B_X = 0$, and $B_Y = 1$, which implies that in this process we have $\Delta B = 1$.

3.2. C-Symmetry and CP-Symmetry Violations

We need processes that discriminate between baryons and antibaryons; otherwise the process $X \to Y + \bar{b}$ (for which $\Delta B = -1$) would be as likely as $X \to Y + b$, which implies that no net baryon number would be generated. More formally, we need to violate processes in which the baryon number is changed and its negative.

We have $CBC^{-1} = -B$ and

$$(CP)\, B\, (CP)^{-1} = -B, \tag{3}$$

while B is here to be understood as an operator for which we have $\langle B \rangle = \mathrm{Tr}(\rho B)$, with ρ the density operator solution of the Liouville equation:

$$\frac{\partial \rho}{\partial t} + i[H, \rho] = 0. \tag{7}$$

If C and CP are exact symmetries, they commute with the Hamiltonian,

$$[H, C] = [H, CP] = 0, \tag{4}$$

and therefore with ρ:

$$\mathrm{Tr}(\rho B) = \mathrm{Tr}\big(CBC^{-1}\rho\big) = -\mathrm{Tr}\big[(CBC^{-1})\, C\rho C^{-1}\big] = -\mathrm{Tr}(\rho B), \tag{8}$$

which implies $\langle B \rangle = 0$, and similarly with CP symmetry. Thus, an exact C or CP symmetry ensures equal production of baryons and antibaryons, preventing the emergence of any net baryon number therefore we need them to be violated for asymmetry.

3.3. Departure from Thermal Equilibrium

If we have thermal equilibrium, the process $X \to Y + b$ is compensated by $Y + b \to X$, and therefore the total baryon number remains zero. This third condition can also be proved more formally. Because we do not have time evolution in equilibrium, we will not use the Liouville equation but instead the CPT theorem, which states that CPT is an exact symmetry:

$$\langle B \rangle_{\text{CPT}} = -\langle B \rangle. \tag{5}$$

If the system is in equilibrium, the density matrix is thermal

$$\rho = \frac{e^{-\beta H}}{Z}, \tag{6}$$

which implies $(CPT)\,\rho\,(CPT)^{-1} = \rho$. Therefore, we need a process out of equilibrium.

4. STANDARD MODEL AND BARYON ASYMMETRY

The Standard Model (SM) provides an elegant explanation for the near conservation of baryon and lepton number. In modern quantum field theory, a model is defined by its field content and a Lagrangian density containing both renormalizable and non-renormalizable operators. Renormalizable terms have couplings with non–negative mass dimension, while non-renormalizable terms have negative mass dimension and are suppressed by powers of a large mass scale M. Their effects at wavelength λ scale as $(\lambda M)^{-n}$, indicating that they are small corrections arising from physics at very high energies.

Within the renormalizable SM Lagrangian, no operators exist that violate baryon number or the individual lepton numbers. However, higher-dimensional operators can be written: dimension five operators (suppressed by $1/M$) violate lepton number, while dimension six operators (suppressed by $1/M^2$) violate baryon number. The dimension five operators naturally generate Majorana masses for neutrinos, and the experimental discovery of neutrino mass provides evidence of such lepton-number–violating physics. The associated mass scale is uncertain but is theoretically expected to lie between 10^{11} and 10^{16} GeV.

The scale M_B of baryon-number violation is more difficult to determine. At minimum, quantum-gravitational effects are expected to violate all global symmetries, implying $M_B \sim M_{\text{Pl}}$, where $M_{\text{Pl}} \approx 10^{19}$ GeV. Dimension–six baryon-violating operators at the Planck scale would lead to proton lifetimes of order 10^{34} years, close to current experimental limits.

If Planck-scale physics were the only source of baryon-number violation, one might imagine that the baryon asymmetry was generated at temperatures near the Planck scale. In such a scenario, violent non-equilibrium gravitational processes could violate baryon number, while CP violation—present in the SM through the Kobayashi–Maskawa mechanism—would supply the required CP asymmetry. In this picture, the observed baryon asymmetry would simply reflect highly complex initial conditions of the Universe, inaccessible to experiment.

However, several arguments disfavor this pessimistic view. First, it is difficult to explain the extremely small observed baryon-to-photon ratio as a natural outcome of Planck-scale dynamics. Second, strong evidence for cosmic inflation indicates that any pre-inflationary baryon asymmetry would be diluted to negligible levels. Third, many extensions of the SM predict new baryon- and lepton-number–violating interactions at scales well below the Planck scale, and some experimental hints support the existence of such physics.

These considerations motivate the hope that the baryon asymmetry may be computable from concrete particle physics mechanisms operating at energies much lower than $M_{\rm Pl}$. Such mechanisms could, in principle, be tested indirectly through cosmological observations or directly through the discovery of new particles and interactions.

Moreover there are quite a few theoretical models which predict that baryonic charge is indeed non-conserved. To start with, there are grand unification theories which put quarks and leptons on equal footing (into the same particle multiplet). Thus there should be be transitions between quarks and leptons which break both baryon and lepton number conservation. This would give rise to proton decay or to neutron-antineutron oscillations,unfortunately not yet discovered by experiment. A plethora of supersymmetric models also predict baryonic charge non-conservation which could occur at the energies below the grand unification scale, $M_{GUT} = 10^{15} - 10^{16}$GeV and potentially be more dangerous for proton decay. Moreover the standard electroweak theory predicts non-conservation of baryonic charge through quantum corrections. This non-conservation is negligibly small at low energies but could be very much enhanced at high temperatures comparable with the electroweak scale. Thus we can conclude that baryonic charge is most probably non-conserved. Manifestation of its non-conservation are strongly suppressed at low energies but at high energies or temperatures, which existed in the early universe, the processes with a change in B might be efficient and produce an excess of baryons over antibaryons.

Several mechanisms have been proposed to understand baryon asymmetry such as Planck-scale baryogenesis, Baryogenesis in GUT theories, Electroweak Baryogenesis, Baryogenesis via Leptogenesis and Affleck-Dine Mechanism being the popular ones. We will discuss some of these in further sections. But first let's overview the cosmology timescale for production of this asymmetry.

5. COSMOLOGY OVERVIEW

Our understanding of the big bang cosmology is based on several key observational pillars. The first is the Hubble expansion, which allows the reconstruction of the Universe's evolution back to a few billion years after the big bang. A second important observable is the cosmic microwave background radiation (CMBR), a relic from the epoch $\sim 10^5$ years after the big bang, when electrons and nuclei combined to form neutral atoms. A third is the primordial abundances of the light elements, produced at temperatures near 1 MeV. Observations of primordial deuterium, together with big-bang nucleosynthesis (BBN) theory, provide an accurate measurement of the baryon-to-photon ratio, in striking agreement with that inferred from CMBR anisotropies:

$$\Omega_B h^2 = 0.0214 \pm 0.002 \quad \text{(BBN)}, \qquad \Omega_B h^2 = 0.0224 \pm 0.0009 \quad \text{(CMBR)}.$$

Measurements of temperature fluctuations in the CMBR (BOOMERANG, MAXIMA, DASI, WMAP) show that, on large scales, the Universe is extraordinarily homogeneous and isotropic. This justifies describing the spacetime geometry using a Robertson-Walker metric,

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2\right], \tag{7}$$

where $R(t)$ is the scale factor, $H = \dot{R}/R$ is the Hubble parameter, and k denotes the curvature.

Inflation provides a compelling explanation for the Universe's homogeneity, flatness, and the origin of the observed density perturbations [7]. During inflation, the scale factor grew exponentially, enlarging a microscopic region to the size of the observable Universe. This rapid expansion drives the curvature parameter to $k = 0$, consistent with observations, and stretches initial quantum fluctuations into the nearly scale-invariant CMBR anisotropies. Inflation also dilutes any preexisting relics, such as magnetic monopoles or baryon asymmetry, by enormous factors ($\sim e^{60}$).

Most inflationary models involve a scalar field the, inflaton with a very flat potential. Such flat directions arise naturally in supersymmetric theories, which also provide candidates for dark matter. However, inflation typically ends with reheating, during which inflaton decays repopulate the Universe and produce a thermal bath. Constraints from gravitino overproduction in supersymmetric models often limit the reheating temperature to $T_{\mathrm{RH}} \lesssim 10^9$ GeV. This restriction has important consequences for viable baryogenesis mechanisms.

A convenient narrative for cosmic history is as follows:

- Before $t \sim 10^{-25}$ s, the Universe was highly inhomogeneous with extremely large energy density.
- Inflation began around $t \sim 10^{-25}$ s, driven by slow roll of the inflaton field.
- The scale factor increased by at least e^{60}, diluting all conserved or approximately conserved quantities (including baryon number) by enormous factors.
- Inflation ended when the inflaton reached the minimum of its potential, reheating the Universe to a high temperature set by its decay rate.

- The baryon asymmetry must therefore have been generated *after* inflation. Any upper bound on the reheating temperature directly restricts which baryogenesis scenarios are viable.

Hence, standard cosmology together with the success of inflation provides a coherent framework linking the CMBR, BBN, large-scale structure, and the thermal history of the Universe. It also constrains the possible epochs during which the matter-antimatter asymmetry could have been generated.

6. GRAND UNIFIED THEORIES (GUT) BARYOGENESIS

One of the earliest and conceptually simplest mechanisms for generating the baryon asymmetry of the Universe arises from the decays of superheavy particles, typically the gauge or Higgs bosons predicted in Grand Unified Theories (GUTs) [7]. These heavy bosons, conventionally labeled as X and $\bar{X}$, have masses of order 10^{15}–10^{16} GeV and naturally violate baryon number. In the early Universe, such bosons may have existed with number densities exceeding their thermal equilibrium values, thereby satisfying the non-equilibrium condition required by the Sakharov criteria. Their subsequent decays into quarks and leptons can then lead to a net baryon excess.

In the simplest setup, a charge-symmetric initial population is assumed, with $n_X = n_{\bar{X}}$ and no other particle species present. The relevant decays involve two baryon-number–violating channels,

$$X \to qq, \qquad X \to q\bar{\ell},$$

and their charge-conjugate counterparts,

$$\bar{X} \to \bar{q}\bar{q}, \qquad \bar{X} \to \bar{q}\ell.$$

If C and CP are violated, the partial decay widths of X and $\bar{X}$ into these channels differ. This asymmetry may be parameterized through small quantities Δ_q and Δ_ℓ, such that

$$\Gamma_{X\to qq} = (1+\Delta_q)\Gamma_q, \qquad \Gamma_{X\to q\bar{\ell}} = (1-\Delta_\ell)\Gamma_\ell, \tag{8}$$

$$\Gamma_{\bar{X}\to\bar{q}\bar{q}} = (1-\Delta_q)\Gamma_q, \qquad \Gamma_{\bar{X}\to\bar{q}\ell} = (1+\Delta_\ell)\Gamma_\ell. \tag{9}$$

CPT symmetry requires the total decay widths of X and $\bar{X}$ to be identical, which imposes the condition

$$\Delta_q\Gamma_q = \Delta_\ell\Gamma_\ell. \tag{10}$$

Thus the net CP violation manifests through an imbalance in specific decay channels rather than through the total rate.

If the decay products quickly thermalise by either through interactions with the plasma or through the rapid expansion of the Universe, then baryon number becomes effectively conserved at later times, preventing subsequent washout. Under these circumstances, the baryon asymmetry produced through the decays can be expressed as:

$$\eta_\beta \simeq \frac{\frac{4}{3}\Delta_q\Gamma_q - \frac{2}{3}\Delta_\ell\Gamma_\ell}{\Gamma_{\rm tot}}\frac{n_X}{n_0}, \tag{11}$$

where n_X is the initial abundance of heavy bosons and n_0 represents the number density of the light degrees of freedom after thermalisation. This expression highlights the dependence of the asymmetry on the CP-violating parameters, the branching fractions of the decay channels, and the deviation of the X abundance from equilibrium.

An important observation is that inverse decays (such as $qq \to X$) do not erase the generated asymmetry. Because of CPT invariance, these inverse processes produce the same sign of baryon number as the direct decays and therefore cannot cancel the net baryon excess. Instead, the dominant washout processes arise from baryon-number–violating $2 \to 2$ scatterings mediated by virtual X exchange [8].

The viability of this mechanism depends crucially on establishing a non-equilibrium abundance of heavy particles. For extremely massive GUT bosons, thermal production is inefficient at early times because the expansion rate of the Universe can exceed the interaction rates required to maintain equilibrium. If the maximum temperature after reheating never reaches the GUT scale, thermally produced X bosons remain exponentially suppressed. Nevertheless, a substantial non-equilibrium population can still arise from inflaton decay after inflation. Moreover, GUT-scale scenarios face the well known gravitino overproduction problem: high reheating temperatures can generate too many gravitinos, potentially conflicting with nucleosynthesis constraints. Thus, while the decay of superheavy GUT bosons provides a natural and elegant pathway for baryogenesis satisfying all three Sakharov conditions and fitting neatly within grand unified frameworks, there remain several theoretical and cosmological challenges that disfavor or constrain this mechanism.

7. ELECTROWEAK BARYOGENESIS

Electroweak baryogenesis (EWBG) is an appealing and experimentally testable scenario in which the baryon asymmetry of the Universe is generated during the electroweak phase transition (EWPT), at temperatures of order $T \sim 100$ GeV. In this framework, all three Sakharov conditions—baryon number violation, C and CP violation, and departure from thermal equilibrium—can, in principle, be satisfied by the electroweak sector of the Standard Model or its extensions [9]. This makes EWBG an attractive alternative to high-scale mechanisms such as GUT baryogenesis or leptogenesis, because it operates at energies accessible to collider and precision experiments.

A central ingredient of EWBG is the presence of baryon-number–violating processes known as sphaleron transitions. These arise from the nontrivial vacuum structure of the $SU(2)_L$ gauge theory and mediate transitions between gauge vacua differing by one unit of Chern–Simons number. At high temperature, before electroweak symmetry breaking, sphaleron processes are unsuppressed and efficiently violate $B + L$ while conserving $B - L$. Their transition rate is parametrically

$$\Gamma_{\rm sph} \sim \kappa(\alpha_W T)^4 \exp\left(-\frac{E_{\rm sph}(T)}{T}\right), \tag{12}$$

where $E_{\rm sph}(T)$ is the sphaleron energy barrier and $\alpha_W = g^2/4\pi$. Once the Higgs field acquires a vacuum expectation value $v(T)$, the sphaleron energy grows approximately as

$$E_{\rm sph}(T) \sim \frac{4\pi v(T)}{g}, \tag{13}$$

rendering sphaleron transitions exponentially suppressed in the broken phase. Successful EWBG requires sphalerons to remain active in the symmetric phase in front of the advancing bubble walls, but to be quenched inside the broken phase so that the generated baryon asymmetry is not washed out. This requirement leads to the well-known washout condition

$$\frac{v(T_c)}{T_c} \gtrsim 1, \tag{14}$$

where T_c is the critical temperature. In the Standard Model with $m_h = 125$ GeV, this condition is not satisfied, providing the first indication that EWBG cannot proceed within the minimal electroweak theory.

In addition to baryon-number violation, EWBG requires a strongly first-order electroweak phase transition to provide the necessary deviation from thermal equilibrium. At finite temperature, the Higgs effective potential can be written as

$$V_{\rm eff}(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4, \tag{15}$$

where the thermal cubic term proportional to $-ET\phi^3$ creates a barrier between the symmetric and broken minima and drives a first-order transition. During such a transition, bubbles of the broken phase nucleate and expand, sweeping the Higgs vacuum expectation value across the plasma. However, in the Standard Model the coefficient E is too small, and for the observed Higgs mass the transition is a crossover rather than first-order. This failure of the SM to realise a first-order transition is the second major obstacle for electroweak baryogenesis.

A third essential ingredient is CP violation. As bubble walls propagate through the plasma, CP-violating interactions generate chiral charge asymmetries in front of the wall. These typically arise from space-dependent complex mass terms, $m(z)$, whose phases vary across the wall, leading to a CP-violating source term of the form

$$S_{\rm CP}(z) \propto {\rm Im}[m^*(\partial_z m)]\,. \tag{16}$$

The resulting left-handed charge densities diffuse into the symmetric phase, where sphalerons convert them into baryon number according to

$$\frac{dn_B}{dt} \sim \Gamma_{\text{sph}}\,\mu_L, \tag{17}$$

with μ_L the chemical potential for left-handed fermions. Once the plasma enters the broken phase, sphaleron processes shut off and the produced baryon asymmetry becomes frozen.

The final baryon-to-entropy ratio is obtained by solving the coupled transport equations describing diffusion, particle number densities, and sphaleron conversion. A representative expression takes the form

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{135\,\Gamma_{\text{sph}}}{4\pi^2 g_* v_w} \int_0^\infty dz\,\mu_L(z)\,e^{-\nu z}, \tag{18}$$

where v_w is the bubble wall velocity, g_* the number of relativistic degrees of freedom, and ν parameterises sphaleron suppression inside the wall. Producing the observed value $\eta_B \simeq 6 \times 10^{-10}$ requires an interplay of a sufficiently strong first-order transition, appropriate diffusion dynamics, and sizable CP-violating phases.

Electroweak baryogenesis is therefore theoretically attractive but impossible to realise in the minimal Standard Model for two reasons: the electroweak transition is not strongly first-order, and the CKM phase provides insufficient CP violation, yielding $\eta_B \sim 10^{-20}$. Consequently, viable realisations require physics beyond the Standard Model. Several well-motivated extensions achieve this, including two-Higgs-doublet models (2HDMs), supersymmetric theories such as the MSSM, and singlet-extended Higgs sectors like the NMSSM. These models can simultaneously strengthen the phase transition—through modified scalar thermal potentials or additional scalar degrees of freedom—and introduce new CP-violating phases, for example in the Higgsino–gaugino or scalar sectors. However, such extensions face tight constraints from collider measurements, Higgs property determinations, and especially electric dipole moment (EDM) bounds, which can severely restrict the size of new CP-violating interactions.

8. LEPTOGENESIS

Leptogenesis is one of the most compelling and robust mechanisms for explaining the baryon asymmetry of the Universe (BAU). It exploits the fact that electroweak sphalerons violate $B + L$ while conserving $B - L$, so that any primordial lepton asymmetry generated in the early Universe can be partially converted into a baryon asymmetry. This ties the origin of ordinary matter directly to neutrino physics and, in particular, to the existence of heavy right–handed Majorana neutrinos predicted in Type-I seesaw extensions of the Standard Model (SM) [10]. The discovery of neutrino masses and mixings provides strong motivation for this framework, since the seesaw mechanism that explains their smallness naturally introduces the heavy degrees of freedom required for Leptogenesis.

In the unbroken electroweak phase at high temperatures, sphaleron processes are rapid compared to the Hubble expansion, enforcing chemical equilibrium among baryon, lepton, and Higgs number densities. These equilibrium constraints relate a primordial $B-L$ asymmetry to the final baryon asymmetry after sphaleron freeze-out. For a theory with n_f fermion families and n_H Higgs doublets, one finds

$$B = \left(\frac{8n_f + 4n_H}{22n_f + 13n_H}\right)(B-L), \tag{19}$$

so that in the Standard Model, with $n_f = 3$ and $n_H = 1$,

$$B = \frac{28}{79}(B-L). \tag{20}$$

Thus, generating a nonzero $(B-L)$ asymmetry before the electroweak phase transition automatically yields a nonzero baryon asymmetry.

The simplest and most widely studied realization of leptogenesis introduces heavy right–handed Majorana neutrinos N_i, with masses M_i, which couple to lepton doublets via Yukawa interactions,

$$\mathcal{L} \supset h_\nu^{\alpha i}\, \bar{\ell}_\alpha\, \tilde{\Phi}\, N_i + \frac{1}{2}M_i\, \overline{N_i^c} N_i + \text{h.c.}, \tag{21}$$

where $\tilde{\Phi} = i\sigma_2\Phi^*$. After electroweak symmetry breaking, these interactions generate Dirac masses

$$m_D = h_\nu \langle\Phi\rangle, \tag{22}$$

and integrating out the heavy N_i yields the familiar Type-I seesaw formula,

$$m_\nu \simeq -m_D M^{-1} m_D^T, \tag{23}$$

which naturally explains the smallness of neutrino masses for M_i in the range 10^{10}–10^{15} GeV. The heavy Majorana neutrinos decay out of equilibrium through

$$N_i \to \ell_\alpha + \Phi, \qquad N_i \to \bar{\ell}_\alpha + \Phi^\dagger, \tag{24}$$

violating lepton number by $\Delta L = \pm 1$. A CP asymmetry is generated by the interference of tree-level and one-loop diagrams (both vertex and self-energy corrections), leading to an asymmetry parameter for the lightest state N_1,

$$\epsilon_1 = \frac{\Gamma(N_1 \to \ell\Phi) - \Gamma(N_1 \to \bar{\ell}\Phi^\dagger)}{\Gamma(N_1 \to \ell\Phi) + \Gamma(N_1 \to \bar{\ell}\Phi^\dagger)}. \tag{25}$$

In terms of the Yukawa couplings, this asymmetry is given by

$$\epsilon_1 = \frac{1}{8\pi(hh^\dagger)_{11}} \sum_{j\neq 1} \mathrm{Im}\big[(hh^\dagger)^2_{1j}\big]\ f\left(\frac{M_j^2}{M_1^2}\right), \tag{26}$$

where $f(x)$ includes both vertex and self-energy loop contributions. Notably, if two heavy neutrinos are nearly degenerate in mass, the self-energy contribution becomes resonantly enhanced, leading to "resonant Leptogenesis," in which ϵ_1 can approach $\mathcal{O}(1)$ even for M_1 near the TeV scale. The out-of-equilibrium condition for successful Leptogenesis requires the decay width of N_1 at $T \sim M_1$ to satisfy

$$\Gamma_{N_1}(T \sim M_1) \lesssim H(T = M_1), \tag{27}$$

which constrains the magnitude of the neutrino Yukawa couplings relative to their masses.

The generation of the lepton asymmetry is governed by Boltzmann equations describing the number densities of N_1 and the lepton asymmetry. These take the schematic form,

$$\frac{dn_{N_1}}{dt} + 3Hn_{N_1} = -\gamma_D(n_{N_1} - n_{N_1}^{\mathrm{eq}}), \qquad \frac{dn_L}{dt} + 3Hn_L = \epsilon_1\gamma_D(n_{N_1} - n_{N_1}^{\mathrm{eq}}) - Wn_L, \tag{28}$$

where γ_D is the thermally averaged decay rate and W encodes washout contributions from $\Delta L = 1, 2$ scatterings such as

$$\ell H \leftrightarrow \bar{\ell} H^\dagger, \qquad \ell\ell \leftrightarrow HH. \tag{29}$$

In particular, $\Delta L = 2$ washout rates scale as

$$\Gamma_{\Delta L=2} \sim \frac{m_\nu^2}{\langle\Phi\rangle^4} T^3, \tag{30}$$

which implies an approximate upper bound on the neutrino mass scale from the requirement that $\Delta L = 2$ processes remain out of equilibrium around $T \sim 10^{10}$ GeV.

An important refinement of standard leptogenesis involves flavor effects. At temperatures below about 10^{12} GeV, charged–lepton Yukawa interactions come into equilibrium, making the τ (and later μ) flavors distinguishable. Consequently, the total lepton asymmetry must be decomposed into flavor components, each with its own CP asymmetry and washout factor, which can significantly affect the final BAU. Additional interesting possibilities arise in low-scale models such as the νMSM, where GeV-scale sterile neutrinos generate the lepton asymmetry not through out-of-equilibrium decays but via CP-violating oscillations. In these scenarios, the relevant dynamics are described not by simple Boltzmann equations but by quantum kinetic equations for the sterile neutrino density matrix.

After all relevant processes freeze out, the total baryon asymmetry is given by

$$\eta_B = \frac{n_B}{s} = c_{\rm sph} \sum_\alpha \eta_{L_\alpha}(T_{\rm sph}), \tag{31}$$

where $c_{\rm sph} = 28/79$ in the Standard Model sets the conversion factor between lepton and baryon number. The observed value,

$$\eta_B^{\rm obs} = 6.1^{+0.3}_{-0.2} \times 10^{-10}, \tag{32}$$

can be reproduced across a wide region of parameter space. Hence, leptogenesis provides a natural and compelling link between the cosmic baryon asymmetry and the origin of neutrino masses, offering multiple realizations from high-scale seesaw models to TeV-scale resonant scenarios and low-scale sterile neutrino oscillation models that remain consistent with current data and promise rich interplay with future neutrino and collider experiments.

9. AFFLECK-DINE BARYOGENESIS

Affleck-Dine (AD) baryogenesis is a powerful and highly flexible mechanism for generating the baryon asymmetry of the Universe, arising naturally in supersymmetric (SUSY) extensions of the Standard Model. A distinctive feature of the Minimal Supersymmetric Standard Model (MSSM) is the presence of numerous *flat directions* in the scalar potential directions in field space for which the renormalizable contributions to the potential vanish, leaving the scalar fields effectively massless. Many of these flat directions carry nonzero baryon or lepton number, making them natural candidates for baryogenesis. Because supersymmetry breaking in the early Universe modifies these potentials through Hubble-induced mass terms and higher-dimensional operators, the dynamics of these flat directions provide an elegant framework in which large baryon or lepton asymmetries can be generated.

In SUSY theories, the scalar potential takes the form

$$V(\phi) = \sum_i |F_i|^2 + \frac{1}{2} \sum_a g_a^2 D_a^2, \tag{33}$$

where F_i and D_a originate from superpotential and gauge interactions, respectively. Flat directions are defined by configurations for which both $F_i = 0$ and $D_a = 0$, such as the combinations $u^c d^c d^c$, QLd^c, or LLe^c. Along these directions, the potential remains essentially flat at the renormalizable level, enabling the scalar field to acquire large vacuum expectation values (VEVs) in the early Universe. During inflation, supersymmetry is broken by the vacuum energy, generating effective mass terms of order the Hubble scale. The full scalar potential along a flat direction typically acquires the structure

$$V(\phi) \simeq (m_\phi^2 - c_H H^2)|\phi|^2 + \left(a_H H \frac{\phi^n}{nM^{n-3}} + \text{h.c.}\right) + \frac{|\phi|^{2n-2}}{M^{2n-6}}, \tag{34}$$

where m_ϕ is the soft SUSY-breaking mass, H the Hubble parameter during inflation, c_H and a_H are order-one constants, M a cutoff scale typically at or near M_{Pl} or a GUT scale, and n labels the leading non-renormalizable operator that lifts the flat direction. The term proportional to a_H is the so-called A-term, which violates baryon or lepton number and introduces CP-violating phases. This term plays a central role in generating the final asymmetry.

During inflation, the negative Hubble-induced mass term $-c_H H^2|\phi|^2$ drives the scalar field to large field values,

$$|\phi|_{\text{inf}} \sim \left(HM^{n-3}\right)^{1/(n-2)}. \tag{35}$$

As the Universe expands and the Hubble parameter decreases, the minimum of the potential gradually shifts back toward the origin. When $H \sim m_\phi$, the soft mass term begins to dominate, and the flat-direction field starts coherent oscillations about the minimum of its potential. Due to the presence of the complex A-term, these oscillations do not proceed along a straight line but instead trace a spiral trajectory in the complex field plane. This spiral motion corresponds to the generation of a conserved baryon or lepton number density,

$$n_{B,L} = i(\dot{\phi}^*\phi - \phi^*\dot{\phi}), \tag{36}$$

analogous to angular momentum in field space. The CP-violating torque induced by the A-term ensures that the direction of rotation, and thus the sign of the generated asymmetry, is fixed. An approximate expression for the asymmetry generated at the onset of oscillations is

$$n_{B,L}(t_{\text{osc}}) \simeq \beta\, m_\phi |\phi_{\text{osc}}|^2 \sin\delta, \tag{37}$$

where β denotes the baryon or lepton charge of the flat direction and δ is an effective CP-violating phase.

Once oscillations commence, the flat-direction condensate behaves as a coherent state of nonrelativistic particles carrying baryon number. As the Universe continues to expand, this condensate eventually decays through Yukawa or gauge interactions into quarks, leptons, and their superpartners. The decay transfers the stored asymmetry to the thermal plasma, with the comoving baryon number subsequently redshifting as

$$n_B(t) = n_B(t_{\text{osc}}) \left(\frac{a_{\text{osc}}}{a(t)}\right)^3. \tag{38}$$

If the flat direction carries lepton number instead of baryon number, electroweak sphalerons partly convert the resulting lepton asymmetry into a baryon asymmetry according to

$$B = -\frac{28}{79} L. \tag{39}$$

After reheating, the baryon-to-entropy ratio becomes

$$\eta_B \equiv \frac{n_B}{s} \simeq \frac{\beta T_{\mathrm{RH}} |\phi_{\mathrm{osc}}|^2 \sin\delta}{m_\phi M_{\mathrm{Pl}}^2}, \tag{40}$$

which can naturally reproduce the observed value $\eta_B \sim 10^{-10}$ for plausible choices of the reheating temperature, flat-direction VEV, and CP-violating phase. The physical picture underlying the Affleck-Dine mechanism is intuitive: one may imagine a scalar field rolling along a nearly flat valley in field space during the early Universe. As the potential becomes slightly tilted and twisted by CP-violating A-terms, the field begins to spiral toward the origin, storing baryon number as angular momentum in field space. When this spiral collapses into particles via condensate decay, the baryon asymmetry becomes imprinted on the Universe.

Affleck-Dine baryogenesis offers several notable advantages. It can easily generate very large asymmetries, which is particularly useful if subsequent entropy production dilutes the baryon number. The mechanism arises naturally from generic features of SUSY models, especially the ubiquitous presence of flat directions, and it is fully compatible with inflationary cosmology, where large field values and coherent oscillations are common. Moreover, AD baryogenesis remains effective even at relatively low reheating temperatures, making it an especially robust scenario in high-scale or low-scale cosmological models alike. For these reasons, the Affleck-Dine mechanism continues to stand as one of the most versatile and theoretically appealing explanations for the origin of the matter-antimatter asymmetry.

10. OTHER MODELS

In addition to the mainstream mechanisms such as GUT baryogenesis, electroweak baryogenesis, leptogenesis, and Affleck-Dine baryogenesis, several alternative scenarios have been proposed and are presented as following. Many of these appear naturally in extensions of the Standard Model.

10.1. Spontaneous Baryogenesis

If a global symmetry associated with baryon number is spontaneously broken, the resulting Goldstone field θ may couple derivatively to the baryon current:

$$\mathcal{L} \supset \frac{1}{f} \partial_\mu \theta \, J_B^\mu. \tag{41}$$

A nonzero $\dot{\theta}$ behaves like an effective chemical potential for baryon number, allowing baryogenesis even in thermal equilibrium.

10.2. Inflaton or Moduli Decay

Scalar fields such as the inflaton or moduli can decay asymmetrically if their decay products violate baryon number and CP. The baryon asymmetry is roughly:

$$\eta_B \sim \epsilon_B \frac{T_{\mathrm{RH}}}{m_\phi}, \tag{42}$$

where ϵ_B is the CP asymmetry. Such scenarios are relevant when the reheating temperature is too low for thermal baryogenesis.

10.3. Baryogenesis from Primordial Black Holes

Primordial black holes (PBHs) evaporate via Hawking radiation, potentially producing baryon asymmetry if baryon- or CP-violating interactions occur near the evaporation endpoint. The mechanism is largely independent of the thermal history prior to evaporation.

10.4. CPT-Violating Baryogenesis

Small CPT-violating energy splittings between baryons and antibaryons,

$$\Delta E = E_b - E_{\bar{b}} \neq 0, \tag{43}$$

can generate an asymmetry without requiring CP violation. Although strongly constrained, such models relax one of Sakharov's conditions.

10.5. Topological Defect Baryogenesis

Cosmic strings, domain walls, or monopoles formed during phase transitions may create out-of-equilibrium regions or enhance sphaleron transitions. CP-violating scattering off defect cores can generate a baryon asymmetry.

10.6. Asymmetric Dark Matter Baryogenesis

A shared mechanism may generate both baryonic and dark matter asymmetries through transfer operators linking the visible and dark sectors:

$$\mathcal{O} \sim \frac{1}{M^n}(qqq\chi). \tag{44}$$

Such models explain $\Omega_{\text{DM}} \approx 5\Omega_b$ naturally.

11. CONCLUSION

Taken together, the comparative picture of all the proposals indicates no unique, universally robust single solution preferred by theory alone; instead, each mechanism occupies a distinctive niche. GUT baryogenesis links to unification and high-scale physics but faces inflation and reheating tensions; Electroweak Baryogenesis is tightly predictive and experimentally accessible but requires beyond–SM Higgs/CP structure; Leptogenesis is minimal and naturally connected to neutrino masses but is generically high-scale unless resonant/low-scale variants apply; Affleck-Dine benefits from supersymmetric flat directions and can produce large asymmetries consistent with inflationary cosmology but depends on SUSY model details; the other mechanisms provide flexible alternatives that can operate under exceptional cosmological conditions or produce novel observational signatures. A more detailed reviews of all these mechanisms are given in [11–15] .

In conclusion, current theoretical and observational constraints favor two broad lessons. First, mechanisms that naturally incorporate or explain neutrino masses (Leptogenesis) and those that are compatible with inflationary cosmology and suppressed washout (Affleck-Dine and certain non-thermal scenarios) present the most attractive frameworks from the standpoint of plausibility and model-building economy. Second, electroweak baryogenesis—while increasingly constrained—remains uniquely valuable due to its testability at collider and electric dipole moment (EDM) experiments. Future progress will be driven by a combination of cosmological probes (primordial gravitational waves from first-order transitions, precision CMB/BBN limits on energy injection), improved neutrino experiments (mass hierarchy, CP phase), dedicated searches for rare low-energy processes (proton decay, n–$\bar{n}$ oscillations), and direct searches for the new particles and CP-violating phases required by these models. Confronting specific baryogenesis scenarios with these diverse experimental inputs is the most promising route to discriminating among candidate mechanisms and ultimately identifying the origin of the matter-antimatter asymmetry.

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