The Baryon Asymmetry Problem: A Review of Theories and Controversies

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I. Abstract:

The baryon asymmetry problem, which is also known as the matter–antimatter asymmetry, is one of the most significant unresolved questions in cosmology and particle physics. Observations indicate that the universe contains far more matter than antimatter despite the Big Bang producing them in nearly equal amounts. Understanding this imbalance is of utmost importance, as it is behind the very existence of galaxies, stars and planets. This paper reviews the leading theoretical explanations, including electroweak baryogenesis, leptogenesis, and Grand Unified Theory (GUT) baryogenesis, evaluating their mechanisms, strengths, and limitations while providing a speculative hybrid synthesis. Observational evidence from the cosmic microwave background, Big Bang nucleosynthesis, and recent measurements of CP violation in baryons provides critical constraints on these models. The paper also discusses the challenges and controversies surrounding baryogenesis such as insufficient Standard Model CP violation, theoretical uncertainties, and experimental limitations.

Keywords: Baryogenesis, Sakharov Condition, CP Violation, Baryon Number Violation, Electroweak Baryogenesis, Leptogenesis, GUT Baryogenesis, Heavy Right-Handed Neutrinos, Sterile Neutrinos, High-Scale Baryogenesis, Low-Scale Baryogenesis.

II. Observational Evidence:

The baryon asymmetry problem has become prominent due to the following important observations. The value of the baryon-to-photon ratio is found to be about 6.14×10^{-10} by CMB observations, establishing a slight predominance of baryons over antibaryons during the early universe (Aghanim et al., 2020). Supplementing this finding are precise determinations of the universe's matter composition by the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellite projects, which demonstrate that baryonic matter accounts for about 5% of the total energy density of the universe, as accurately predicted by Big Bang Nucleosynthesis (Aghanim et al., 2020).

Recent experimental developments have also clarified this topic. In 2025, for the first time ever at CERN's LHCb detector, charge-parity differences were found in the decay of beauty-lambda baryons. This experiment demonstrates that charge-parity violation might also play a role in explaining why more matter exists in the universe because it enables a difference in how matter and antimatter undergo decay (LHCb Collaboration 2025).

Collectively, these observations emphasize the existence of a baryon asymmetry in the universe challenging existing models and prompting further theoretical and experimental investigations into its origins.

III. Theoretical Explanations:

1. Sakharov conditions (foundational theory)

Any dynamical explanation of the baryon asymmetry must satisfy the three necessary conditions identified by Andrei Sakharov:

1) *baryon-number* (B) violation,

2) C and CP violation, and

3) departure from thermal equilibrium (Sakharov 1967).

These conditions are not a theory themselves but serve as conditions for viable models, as without processes that change B, an initially symmetric universe cannot produce a net baryon number; without C and CP violation, matter and antimatter would be produced and destroyed at identical rates; and without an out of equilibrium epoch, the CPT theorem and detailed balance drive any small asymmetry back to zero (Sakharov 1967; Kolb and Turner 1990). Modern model building therefore tests each candidate mechanism against these three criteria and asks whether the required rates and CP phases can be large enough in the relevant cosmological epoch to produce the observed baryon-to-photon ratio $\eta_B \simeq 6\times10^{-10}$ (Kolb and Turner 1990; Bödeker and Buchmüller 2021).

2. Electroweak baryogenesis

a. Overview and Mechanism

Electroweak baryogenesis (EWBG) proposes that the baryon asymmetry was produced during the *electroweak phase transition* (EWPT) at temperatures of order 100 GeV. In EWBG the Standard Model (SM) electroweak interactions supply all three Sakharov ingredients, nonperturbative sphaleron processes violate B, new CP-violating interactions near the electroweak scale provide the required C/CP asymmetry, and a first-order EWPT produces expanding phase boundaries (bubble walls) that drive departures from thermal equilibrium (Morrissey and Ramsey-Musolf 2012; Bödeker and Buchmüller 2021).

b. Microphysics

During a strong first-order EWPT, bubbles of the broken phase nucleate and expand through the symmetric plasma. CP-violating interactions in or near the bubble walls create chiral (particle/antiparticle) asymmetries in front of the wall, these asymmetries bias sphaleron transitions in the symmetric phase to convert chiral charge into net baryon number. When that baryon number is swept into the broken phase where sphalerons are suppressed, it is (partially) preserved, leaving a net BAU (Morrissey and Ramsey-Musolf 2012).

c. Strengths and Challenges

EWBG is promising since it ties baryogenesis to weak-scale physics and so is in principle testable at colliders and in *electric dipole moment* (EDM) experiments (Morrissey and Ramsey-Musolf 2012). However, in the minimal SM the EWPT is a crossover for the observed Higgs mass, and SM CP violation from the CKM matrix is too small to generate the observed ηB (Riotto and Trodden 1999; Morrissey and Ramsey-Musolf 2012). Consequently viable EWBG requires beyond-Standard-Model ingredients (additional scalar fields, new fermions, or strong dynamics) that produce a strong first-order transition and extra CP phases. Current collider data and stringent EDM limits have excluded or strongly constrained many concrete EWBG realizations, leaving only special corners of model space (Bödeker and Buchmüller 2021; Morrissey and Ramsey-Musolf 2012).

In particular, Two-Higgs-Doublet Models (2HDM) with sizable CP violating scalar sector phases are also strongly squeezed by EDM limits, though specific flavour structures or alignment limits can leave viable pockets. By contrast, singlet-extended models (SM+S, i.e., the Standard Model plus a gauge-singlet scalar) can more readily produce a strong first-order EWPT while partially evading EDM constraints if the dominant CP violation is sequestered in the singlet sector or is predominantly spacetime-dependent across the bubble wall.

3. Leptogenesis

a. Overview and Mechanism

Leptogenesis converts a primordial lepton asymmetry into a baryon asymmetry through electroweak sphalerons. In the archetypal scenario, heavy right-handed neutrinos decay out of equilibrium and with CP-violating asymmetries to produce a net lepton number; anomalous electroweak processes (sphalerons) then partially reprocess B and L, converting some of the lepton excess into baryons (Fukugita and Yanagida 1986; Luty 1992; Strumia 2006). Modern treatments emphasise that this asymmetry is not created in a single “one-flavour” approximation, as at temperatures below about 10^{12} to 10^{9} GeV individual charged-lepton flavours differentiate, and the produced asymmetry is tracked separately for each flavour. Due to this, certain flavours can be washed out more efficiently than others, and CP violation can appear in flavour specific decay channels even when the total asymmetry would vanish in the unflavoured limit (Nardi et al. 2006; Abada et al. 2006).

b. Microphysics and Realizations

Thermal (or "vanilla") leptogenesis assumes heavy right-handed neutrinos with masses well above the electroweak scale (often near 10^9–10^{12} GeV). Their out-of-equilibrium CP-violating decays create $L \neq 0$; sphalerons operating at $T \gtrsim 100$ GeV convert ΔL partially into ΔB with a calculable conversion factor (Fukugita and Yanagida 1986; Strumia 2006). Variants include resonant leptogenesis (nearly degenerate heavy neutrinos allow successful baryogenesis at lower temperatures) and leptogenesis via oscillations of GeV scale sterile neutrinos (Akhmedov et al. 1998; Bödeker and Buchmüller 2021).

A major active debate concerns the correct implementation of finite-temperature quantum field theory in the early Universe: thermal masses, thermal cuts, and HTL (hard thermal loop) corrections modify decay rates, CP-violating loop functions, and washout processes. These thermal corrections can change the viable parameter space significantly and are treated differently in various ways (Giudice et al. 2004; Beneke et al. 2010). Additively, flavour covariant kinetic equations rather than simple Boltzmann equations are required when quantum correlations between flavours persist, making the treatment of flavour dynamics a central theoretical uncertainty.

c. Strengths and Challenges

Leptogenesis is appealing because it links the BAU to neutrino mass physics and the seesaw mechanism, offering a unified explanation for two otherwise separate puzzles (Fukugita and Yanagida 1986; Kolb and Turner 1990). Many leptogenesis implementations naturally produce the right order of magnitude for η_B and are compatible with current neutrino data. The main challenge is direct testability: the heavy scales often lie far above collider reach. Still, low-scale variants and the connection to neutrino parameters mean that improvements in neutrino experiments, searches for sterile neutrinos, and cosmological bounds on neutrino masses can probe parts of the leptogenesis parameter space (Strumia 2006; Bödeker and Buchmüller 2021).

4. GUT baryogenesis:

a. Overview and Mechanism

Grand Unified Theory (GUT) baryogenesis was among the earliest proposals, heavy GUT bosons (X, Y) mediate B-violating decays in the very early universe (temperatures near the GUT scale, $\sim 10^{15}$–10^{16} GeV), and if these decays violate CP and occur out of equilibrium, they produce a net baryon number leading to the asymmetry (Kolb and Turner 1990; Riotto and Trodden 1999).

b. Microphysics and Variants

In SU(5) or SO(10) models, X-boson decays directly change baryon number. The magnitude of the generated asymmetry is model dependent and can naturally explain the order of magnitude of η_B, but there are two historical complications. First, electroweak sphalerons at temperatures below the GUT scale conserve B–L but violate B+L; if a GUT mechanism produces only B (with B–L = 0) sphaleron processes can erase the asymmetry (Kuzmin, Rubakov, and Shaposhnikov 1985; Riotto and Trodden 1999). Second, many simple GUT models predict proton decay or other signatures already tightly constrained experimentally, limiting available model space (Kolb and Turner 1990; Bödeker and Buchmüller 2021). Some modern GUT scenarios circumvent these issues by producing a B–L asymmetry or by using nonthermal production mechanisms (Kolb and Turner 1990; Riotto and Trodden 1999).

c. Strengths and Challenges

GUT baryogenesis links baryon number violation to unification physics and can generate large asymmetries at very high temperatures, but it is difficult to test directly and must contend with sphaleron washout and experimental constraints on GUT physics. Recent work has explored nonthermal production after inflation and connections to gravitational-wave signals from high-scale symmetry breaking as ways to gain observational handles (Riotto and Trodden 1999; Bödeker and Buchmüller 2021).

5. Bubble Assisted Neutrino Oscillation Leptogenesis

(Author's speculative proposal)

While the mechanisms discussed above are usually referred to as different pathways to baryogenesis, it is possible that baryon asymmetry may have risen from interplay between the different processes working simultaneously in the early universe. In this section, the author proposes a hybrid scenario which combines the low-scale neutrino-oscillation leptogenesis with a strong first order electroweak phase transition (EWPT). This scenario referred to here as Bubble Assisted Neutrino Oscillation Leptogenesis is not an established model but a speculative synthesis of existing ideas.

In neutrino oscillation leptogenesis, GeV-scale sterile neutrinos create a lepton asymmetry through CP-violating flavour oscillations in the early universe, without requiring ultra-heavy Majorana masses (Akhmedov et al. 1998; Abada et al. 2006). These oscillations occur out of equilibrium and satisfy key Sakharov conditions although their efficiency is sensitive to thermal corrections, flavour washout, and quantum coherence effects which leads to significant uncertainty (Beneke et al. 2010; Bödeker and Buchmüller 2021).

Separately, electroweak baryogenesis relies on a strong first-order EWPT, during which expanding bubbles of the broken phase provide a departure from equilibrium, while CP-violating interactions near bubble walls bias sphaleron processes in the symmetric phase (Morrissey and

Ramsey-Musolf 2012). Although the minimal Standard Model cannot support such a transition, many extensions allow it.

The speculative proposal advanced here is that sterile neutrino oscillations occurring near electroweak bubble walls experience modified dispersion relations due to the rapidly varying Higgs background. This spacetime dependent environment may enhance effective CP-violating phases or induce resonant behaviour in flavour oscillations which amplifies the lepton asymmetry produced ahead of the wall. Electroweak sphalerons then partially convert this lepton asymmetry into baryon number, which is preserved inside the broken phase where sphaleron rates are suppressed (Kuzmin et al. 1985).

This hybrid mechanism satisfies all three Sakharov conditions and may alleviate electric dipole moment constraints by localising much of the CP violation in the neutrino sector and in spacetime dependent backgrounds (Andreev et al. 2018). Observationally, it predicts a stochastic gravitational-wave background from a strong EWPT and testable signatures of GeV-scale sterile neutrinos, offering a multi-probe pathway to the origin of the baryon asymmetry (Bödeker and Buchmüller 2021).

Note: A quantitative realization of this idea would require a dedicated treatment of coupled neutrino transport and bubble-wall dynamics, which lies beyond the scope of this.

IV. Comparative Evaluation and Observational Signatures:

The four pathways above exemplify two classes: weak-scale mechanisms (electroweak baryogenesis), which are more directly testable in laboratory experiments, and high-scale mechanisms (leptogenesis and GUT baryogenesis), which are more naturally embedded in theories of neutrino masses or unification and might be more likely true but are harder to probe directly (Riotto and Trodden 1999; Bödeker and Buchmüller 2021). Practical discriminants include:

- **Collider and EDM constraints -** EWBG models predict new weak-scale states and extra CP phases; collider searches and EDM bounds have already ruled out large regions of parameter space (Morrissey and Ramsey-Musolf 2012; Bödeker and Buchmüller 2021).

- **Neutrino physics -** Leptogenesis connects to the seesaw and to neutrino mass parameters; improved measurements of neutrino mass ordering, CP phase, and absolute masses can restrict leptogenesis scenarios (Fukugita and Yanagida 1986; Strumia 2006).

- **Cosmological probes -** Precision CMB and large-scale structure measurements fix η_B and constrain extra relativistic species and neutrino masses. Future gravitational-wave observations could probe phase transitions relevant to EWBG or high-scale symmetry breaking (Bödeker and Buchmüller 2021).

- **Low-energy rare processes.** Proton-decay limits constrain simple GUT models, while searches for sterile neutrinos or lepton-number-violating processes (neutrinoless double beta decay) test ingredients of leptogenesis and GUT scenarios (Kolb and Turner 1990; Riotto and Trodden 1999).

V. Controversies and Challenges:

a. Limitations of Standard-Model CP violation

The most fundamental challenge is that the CP violation present in the Standard Model (SM) — encoded in the *Cabibbo–Kobayashi–Maskawa* (CKM) matrix for quarks and the analogous PMNS phases for leptons appears far too small to generate the observed baryon-to-photon ratio, $\eta\_B \simeq 6\times10^{-10}$, in realistic cosmological settings (Gavela et al. 1994; Riotto and Trodden 1999). Quantitative estimates show that quark-sector CP phases produce asymmetries many orders of magnitude below the required value once washout and thermal averaging are accounted for; similarly, although leptonic CP violation could play a role in leptogenesis, the connection between low-energy neutrino phases and the CP violation relevant at high energies is highly model dependent (Strumia 2006; Riotto and Trodden 1999).

Compounding the problem, laboratory limits on flavour-blind CP-violating observables, most notably electric dipole moments (EDMs) strongly constrain many extensions of the SM that would otherwise supply the extra CP needed for baryogenesis. The non-observation of a permanent electron EDM at current sensitivity places tight bounds on new CP phases in weak-scale models, ruling out large portions of parameter space for electroweak baryogenesis unless the model contains mechanisms to suppress low-energy EDM signals (Andreev et al. 2018; Morrissey and Ramsey-Musolf 2012). So, any successful model must thread a narrow needle, that is to produce sufficiently large, cosmologically effective CP violation while evading stringent low-energy constraints.

b. Disagreement among theoretical models and calculational uncertainties

Even within broad classes of mechanisms (electroweak baryogenesis, leptogenesis, GUT baryogenesis), there is wide disagreement about the viability and detailed predictions of competing implementations. Two sources of model-level disagreement are particularly important. First, mechanisms that require new dynamics at high scales (e.g., heavy right handed neutrinos in thermal leptogenesis or X/Y bosons in simple GUTs) suffer from a lack of direct testability: many parameter choices reproduce η_B but are experimentally inaccessible, making the models difficult to falsify (Kolb and Turner 1990; Fukugita and Yanagida 1986). Second, weak-scale scenarios are highly sensitive to nonperturbative, out-of-equilibrium physics (bubble-wall microphysics, transport coefficients, and sphaleron rates). Different treatments of these nonequilibrium processes (semi-classical transport equations, full Kadanoff–Baym approaches, or effective field theory estimates) can yield quantitatively different predictions for the final asymmetry, producing debate about which approximations are reliable (Morrissey and Ramsey-Musolf 2012; Bödeker and Buchmüller 2021).

c. Experimental uncertainties and conflicting data

Progress is limited by several experimental uncertainties and occasional tensions among datasets. Cosmological determinations of the baryon density (from the CMB and Big-Bang nucleosynthesis) are precise and mutually consistent, but they only measure the outcome, not the mechanism. Discriminating among theories therefore depends on indirect probes, improved measurements of neutrino properties (mass scale, mass ordering, and CP phases), stronger limits (or a detection) of EDMs, searches for proton decay (constraining simple GUTs), and collider searches for weak-scale states. At present, many of these probes give only exclusionary information or show limited sensitivity to the most natural regions of parameter space; in some cases different experiments point to tensions in preferred parameter regions for concrete models (Esteban et al. 2020; Andreev et al. 2018).

Finally, experimental claims that might directly support one mechanism over another often demand careful interpretation. Signals of new CP violation at colliders or small anomalies in flavour physics must be cross-checked for statistical robustness and theoretical systematic errors before being taken as evidence for a cosmological role. Until low-energy and astrophysical probes improve their reach, multiple baryogenesis explanations will remain viable and competing.

VI. Implications for Cosmology and Particle Physics:

a. Connection to dark matter and inflation theories

Baryogenesis does not occur in isolation; this is due to the fact that many viable baryogenesis mechanisms are embedded in broader frameworks that also address dark matter and inflation. For example, certain GUT- and inflaton-decay scenarios naturally produce both a baryon asymmetry and a nonthermal dark-matter population, tying the abundance and phase-space properties of dark matter to baryogenesis model parameters (Kolb and Turner 1990; Riotto and Trodden 1999). Similarly, models that invoke heavy particle decays after inflation (nonthermal leptogenesis) link the reheating temperature, the spectrum of relics, and the efficiency of baryon-number generation, so constraints on dark-matter production and isocurvature perturbations translate directly into constraints on baryogenesis model space (Fukugita and Yanagida 1986; Riotto and Trodden 1999).

b. Impact on understanding the early universe's evolution

Which baryogenesis mechanism is correct strongly affects the thermal history of the early universe. A first-order electroweak phase transition would introduce violent out-of-equilibrium dynamics and potentially observable gravitational waves, whereas high-scale leptogenesis or GUT processes place the decisive dynamics at far higher temperatures and earlier times (Morrissey and Ramsey-Musolf 2012; Bödeker and Buchmüller 2021). Thus, determining the origin of the baryon asymmetry would fix (or rule out) classes of phase transitions, constrain reheating and entropy production histories, and inform models of primordial perturbations and relic abundances.

c. Guidance for future experimental and theoretical research

Practical progress requires coordinated probes across disciplines. In particle physics, refined EDM searches, precision collider studies of Higgs and new scalar sectors, and improved neutrino experiments (mass ordering and CP phase) will narrow the parameter space of electroweak and leptogenesis scenarios (Andreev et al. 2018; Strumia 2006). In cosmology, next-generation CMB and large-scale-structure surveys, together with gravitational-wave detectors sensitive to phase-transition signatures, can test predictions unique to particular baryogenesis classes (Bödeker and Buchmüller 2021). Theoretically, advances in nonequilibrium quantum field theory and lattice studies of sphaleron dynamics are essential to reduce systematic uncertainties and turn qualitative models into precision tests. Together, these efforts will transform baryogenesis from a collection of plausible ideas into an experimentally constrained component of the standard cosmological narrative.

VII. Conclusion:

The baryon asymmetry of the universe remains one of the most important open questions in cosmology and particle physics. Observations, including the cosmic microwave background and primordial element abundances, clearly show a small but significant excess of matter over antimatter. While the Standard Model provides some CP violation, it is insufficient to explain the observed asymmetry. Theoretical frameworks such as electroweak baryogenesis, leptogenesis, and GUT baryogenesis offer plausible mechanisms, yet each faces challenges from experimental constraints and model uncertainties to the difficulty of testing high-scale processes. Future progress will rely on a combination of precision experiments, including neutrino measurements, EDM searches, collider studies, and cosmological observations. Solving the baryon asymmetry problem promises not only to explain why matter dominates the universe but also to enhance our understanding of the early universe, fundamental forces, and the connections between particle physics and cosmology.

VIII. References:

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X. Statements and Declaration:

a. Competing Interests

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b. Data Availability

There is no other data associated with this paper.

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