The Matter-Antimatter Asymmetry in the Universe

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The Problem

\[(i\hbar \gamma^\mu \partial_\mu - mc)\psi = 0\]

The Dirac equation treats particles and antiparticles \textit{equally}.

As the early universe cooled and expanded, most of the matter and antimatter produced in the Big Bang should have annihilated before antinucleon freezeout at \(\sim 20\) MeV.

\textbf{Predicted} \(\Omega_{\text{baryon}} \sim 4 \times 10^{-11}\) \quad \textbf{Observed} \(\Omega_{\text{baryon}} \sim 4 \times 10^{-2}\)

\textit{What additional mechanism can account for this 9-orders-of-magnitude difference?}
Approaching a Solution

*Sakharov’s Conditions for producing a baryon asymmetry*

1. Baryon number violation
2. Violation of C and CP
3. Conditions in which processes take place out of thermal equilibrium

*Outline of this talk*

I. Two classes of theories
   i. Baryogenesis
   ii. Leptogenesis
II. Local vs. global asymmetry – does matter dominate the *entire* universe?
III. Observational measurements and limits
Baryogenesis I: Electroweak Baryogenesis

Sakharov’s Conditions

1. Baryon number violation \(\rightarrow\) satisfied by sphaleron transitions \(\checkmark\) (see next slide)
2. Violation of C and CP \(\rightarrow\) satisfied by weak force \(\checkmark\)
3. Conditions in which processes take place out of thermal equilibrium \(\rightarrow\) satisfied if Electroweak Phase Transition was first-order \(\checkmark\) (see below)

Electroweak Phase Transition

- The transition to a phase with massive gauge bosons
- Whether it is first- or second-order depends on the mass of the Higgs boson

Image from Dine et al. (Ref. 2)
**Sphaleron Transitions**

Yang-Mills vacuum structure (non-Abelian gauge theory):

- Transitions among the different ground-state configurations conserve (B-L), but not B and L separately
- The probability of tunneling decreases as the universe cools, and within a given minimum (e.g. the universe today) B and L are conserved separately
- These processes also play an important role in the mechanism of leptogenesis (to be covered later in the talk)
The Downfall of EW Baryogenesis

First-order EWPT requires a light Higgs

- At least in the minimal SM with a single Higgs doublet, the Higgs mass must be less than ~80 GeV for the EWPT to be first-order
- However, the experimental lower limit is ~110 GeV

CP violation in CKM matrix too small

- Standard Model CP violation must involve all three fermion generations
- The lowest-order CP-violating diagram relevant to baryogenesis is suppressed by 12 Yukawa couplings (~10^{-20})

The baryon asymmetry that the SM is capable of producing is far too small – we need to look elsewhere
Baryogenesis II: Higher-Scale Baryogenesis

**Planck-Scale Baryogenesis**
- Quantum theories of gravity are expected to violate all global quantum numbers, including baryon number
- However, Planck scale is $\sim 10^{19}$ GeV; all Planck-scale processes would have occurred before inflation, which would have diluted away any baryon number produced prior

**GUT-Scale Baryogenesis**
- Supersymmetry introduces heavy particles whose decays violate B and CP, and which will occur out of equilibrium as the universe cools below the GUT scale
- GUT scale is $\sim 2 \times 10^{16}$ GeV; same inflation/dilution problem as Planck-scale baryogenesis
- It is possible that the reheating temperature $T_{\text{reheat}}$ after inflation could be high enough for GUT-scale processes to come into play again, but then too many gravitinos would be produced to be consistent with observation (limit: $< 10^9$ GeV)
Can SUSY Save EW Baryogenesis?

Additional sources of CP violation ✓

The addition of the superpartners allows the possibility for a sufficient increase in the magnitude of CP violation present in the theory.

So the trick is ensuring out-of-equilibrium dynamics

First-order EWPT:

A light right-handed stop can allow a Higgs mass of up to \(\sim 115 \text{ GeV}\) in the MSSM, just barely consistent with limits

OR

Inflation:

If, by some fortuitous coincidence, inflation and electroweak symmetry breaking happen concurrently
Baryogenesis III: Affleck-Dine Baryogenesis

Assumes **SUSY** and **inflation**

1. Introduces scalar fields carrying B and L; when supersymmetry is unbroken, the potentials for these fields are nearly flat $\rightarrow$ easily excited

2. Breaks supersymmetry (potentials no longer flat), and introduces B- and CP-violating terms

3. Fields fall down to ground state and decay into particles, carrying over the net baryon number produced
Leptogenesis: Starting from Seesaw

A Dirac mass term couples a right-handed field to a left-handed field or vice versa.

A Majorana mass term couples a right-handed field to another right-handed field or vice versa.

Type I Seesaw introduces heavy right-handed singlet neutrinos as counterparts to the familiar light neutrinos in order to provide a ‘natural’ explanation for the small mass of the neutrino:

\[
\begin{pmatrix}
0 & h_v \nu \\
h_v^T \nu & M_R
\end{pmatrix}
\]

Dirac terms: similar scale to quark, charged lepton sectors

Mass matrix for \((\nu_L, \nu_R)\) system

Majorana term: much heavier, \(M_R >> h_v \nu\)

\[= m_\nu \approx -h_v^2 \nu^2 / M_R \]

* Majorana neutrinos explicitly violate L

* L can be converted to B by sphaleron processes
Leptogenesis: A Simple Model

Add three heavy Majorana neutrinos $N_i$, where $M_1 \ll M_2, M_3$

$N_1$ can decay into e.g. Higgs and (anti)lepton as the universe cools

At tree level the $N_1 \rightarrow$ lepton and $N_1 \rightarrow$ antilepton rates are the same

CP violation arises from interference with higher-order diagrams, which bring in contributions from $N_2, N_3$

Image from Davidson et al. (Ref. 4)
Washout and Flavor Effects

The non-equilibrium dynamics for leptogenesis are provided by the expansion of the Universe – relative rates of processes are crucial.

For convenience, define:

\[
\tilde{m} = \sum \tilde{m}_{\alpha\alpha} = \sum_{\alpha} \frac{\lambda^*_{\alpha 1} \lambda_{\alpha 1} v_u^2}{M_1} = 8\pi \frac{v_u^2}{M_1^2} \Gamma_D,
\]

Higgs vev, \( \approx 174 \text{ GeV} \)

Total decay rate of \( N_1 \)

\[
m_* = 8\pi \frac{v_u^2}{M_1^2} H|_{T=M_1} \approx 1.1 \times 10^{-3} \text{ eV}.
\]

Hubble expansion rate

We can relate this to light neutrino properties:

\[
\tilde{m} > m_{\text{min}} \quad \text{and} \quad \text{“usually”} \quad \tilde{m} \gtrsim m_{\text{sol}}
\]

\[
\tilde{m} > m_* \quad \text{reaches thermal density} \quad n_1 \sim n_{\gamma}
\]

\[
\tilde{m} < m_* \quad \text{“weak washout”} \quad \text{reaches only} \quad n_1 \sim (\tilde{m}/m_\nu)n_{\gamma}
\]

Similarity, relative rates affect which flavor eigenstates are in equilibrium, and calculations are not flavor-covariant \( \rightarrow \) can have quantitative effects.
Leptogenesis: Some Variations

1. Supersymmetric thermal leptogenesis
   • Calculation substantially the same, differs by a few $O(1)$ numerical factors
   • Following the previous simple model, requires $T_{\text{reheat}} > \frac{M_1}{5} (\sim 10^9 \text{GeV}) \rightarrow$ gravitino problem

2. Less hierarchical $N$’s ($N_1 < N_2 < N_3$, but not $N_1 << N_2, N_3$)
   • Decay of heavier $N$’s can start to contribute, relaxing bound on $T_{\text{reheat}}$
   • “A resonant enhancement of the CP asymmetry in $N_1$ decay occurs when the mass difference between $N_1$ and $N_2$ is of the order of the decay widths.” [4]

3. Soft leptogenesis
   • Dominated by $L$- and CP-violating terms involving singlet sneutrinos

4. Dirac leptogenesis
   • Neutrinos are Dirac, no $L$-violation except sphaleron processes
   • Neutrinos’ Yukawa interactions very slow

5. Type II (triplet scalar) and III (triplet fermion) Seesaw
   • Impossible for minimal Type II without SUSY soft leptogenesis
   • Type III places an order-of-magnitude higher lower bound on $T_{\text{reheat}}$
Local vs. Global Asymmetry

In the ‘neighborhood’ of Earth, matter dominates. Is this because:

- There is a **global**, systematic predisposition to matter?
- There is a **local** asymmetry due to spontaneous symmetry breaking, but the universe as a whole has no asymmetry (e.g. is composed of domains of matter and antimatter, similar to unmagnetized iron cooled to $T<T_c$, $B=0$)?

**Signals to look for:**

- Extragalactic photon background from matter-antimatter annihilation at borders between domains
- Antimatter in cosmic rays that may have traveled from antimatter domains
Observations: Diffuse Gamma Spectrum

Assuming γ’s are produced in p̅p annihilation via π⁰ decay, observations of the diffuse γ spectrum indicate limits on the antimatter/matter fraction of:

- ≤10⁻¹⁵ in Galactic molecular clouds
- ≤10⁻¹⁰ in Galactic halo
- ≤10⁻⁵ at the cluster level

This corresponds to a domain size limit of ≥50 Mpc

It is still possible for there to be antimatter domains at the supercluster level, but it looks less and less likely...
Observations: Antiprotons and Positrons

**Figure 3.** Antiproton flux: experimental situation and theoretical predictions

**Figure 4.** Positron fraction experimental situation and theoretical predictions

Both can be produced through interaction of cosmic rays with the interstellar medium, difficult to disentangle primary flux
Observations: Antihelium Limits

Figure from Picozza et al. (Ref. 6)

Antinuclei in the CR flux would be a ‘smoking gun’ for surviving primordial antimatter.

**Antihelium** would be most abundant, and not necessarily indicative of large-scale structures.

Heavier antinuclei would indicate the presence of antimatter stars, in which antinucleosynthesis could occur.

**Figure 2.** Present experimental limits for the antihelium/helium ratio
References


