From neutrino masses to the matter-antimatter asymmetry of the Universe

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Introduction

The Standard Model of strong and electroweak interactions is one of the most successful theories in physics, and the new boson discovered by the LHC could be its last missing piece: the Higgs boson.

Nevertheless the Standard Model fails to account for several observational facts, most notably dark matter, dark energy and the baryon asymmetry (or matter-antimatter asymmetry) of the Universe.

Both dark matter and the BAU require an extension of the Standard Model, which depending on its nature may or may not lead to an observable signal at the LHC or in other experiments.

Neutrino masses (evidenced by the numerous observations of neutrino oscillations) also call for new physics beyond the Standard Model, and may have a common origin with the BAU, thanks to a mechanism known as leptogenesis.
The observed matter asymmetry

Mere observation: the structures we observe in the Universe are made of matter (p, n, e-). No significant presence of antimatter (anti-p, anti-n, e+).

This matter-antimatter asymmetry is measured by the baryon-to-photon ratio (⇒ baryon asymmetry of the Universe = BAU):

\[ \eta \equiv \frac{n_B}{n_\gamma} \sim \frac{n_B - n_{\bar{B}}}{n_\gamma} \]

2 independent determinations of \( \eta \):

(i) light element abundances

(ii) anisotropies of the cosmic microwave background (CMB)
Big Bang nucleosynthesis predicts the abundances of the light elements (D, $^3$He, $^4$He and $^7$Li) as a function of $\eta$. 
The fact that there is a range of values for $\eta$ consistent with all observed abundances ("concordance") is a major success of Big Bang cosmology.

$$\eta = (5.1 - 6.5) \times 10^{-10}$$

- bands = 95% C.L.
- smaller boxes = $\pm 2\sigma$ statistics
- larger boxes = $\pm 2\sigma$ statistics and systematics
Information on the cosmological parameters can be extracted from the temperature anisotropies of the CMB.

In particular, the anisotropies are affected by the oscillations of the baryon-photon plasma before recombination, which depend on \( \eta \) (or \( \Omega_b h^2 \)).

\[
\Rightarrow \quad \eta = (6.04 \pm 0.08) \times 10^{-10} \quad \text{(Planck)}
\]
remarkable agreement between the CMB and BBN determinations of the baryon asymmetry: another success of standard Big Bang cosmology

\[ \eta = (5.1 - 6.5) \times 10^{-10} \quad (\text{BBN}) \]

\[ \eta = (6.04 \pm 0.08) \times 10^{-10} \quad (\text{Planck}) \]

Although this number might seem small, it is actually very large:

in a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance

\[ \frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \approx 5 \times 10^{-19} \]
The necessity of a dynamical generation

In a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance \( n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19} \)

Since at high temperatures \( n_q \sim n_{\bar{q}} \sim n_\gamma \), one would need to fine-tune the initial conditions in order to obtain the observed baryon asymmetry as a result of a small primordial excess of quarks over antiquarks:

\[
\frac{n_q - n_{\bar{q}}}{n_q} \approx 3 \times 10^{-8}
\]

Furthermore, our Universe most probably underwent a phase of inflation, which exponentially diluted the initial conditions

⇒ need a mechanism to dynamically generate the baryon asymmetry

Baryogenesis!
Conditions for baryogenesis

Sakharov’s conditions [1967]:

(i) Baryon number (B) violation

(ii) C and CP violation

otherwise the processes creating baryons and the CP-conjugated processes creating antibaryons would balance each other once integrated over phase space

C [charge conjugation] exchanges a particle with its antiparticle

CP [C combined with a parity transformation, \((t, \vec{x}) \rightarrow (t, -\vec{x})\)] simultaneously reverses the impulsion of the particle

(iii) departure from thermal equilibrium

otherwise the baryons created by some process would be destroyed by the inverse process, resulting in a vanishing net baryon asymmetry
Quite remarkably, the Standard Model (SM) of particle physics satisfies all three Sakharov’s conditions:

(i) B is violated by non-perturbative processes known as sphalerons

(ii) C and CP are violated by SM interactions (CP violation due to the quark mixing phase)

(iii) departure from thermal equilibrium can occur during the electroweak phase transition

→ ingredients of electroweak baryogenesis
Baryon number violation in the Standard Model

The baryon (B) and lepton (L) numbers are accidental global symmetries of the SM Lagrangian ⇒ all perturbative processes preserve B and L

However, B+L is violated at the quantum level (anomaly) ⇒ non-perturbative transitions between vacua of the electroweak theory characterized by different values of B+L [but B-L is conserved]

\[ \Delta B = \Delta L = 3\Delta N_{CS} \]

\[ E_{sph}(T) = \text{energy of the gauge field configuration ("sphaleron") that interpolates between two vacua} \]

In equilibrium above the EWPT [\( T > T_{EW} \sim 100 \text{ GeV} \), \( \langle \phi \rangle = 0 \)]:

\[ \Gamma(T > T_{EW}) \sim \alpha_W^5 T^4 \]

\[ \alpha_W \equiv g^2/4\pi \]

Exponentially suppressed below the EWPT [\( 0 < T < T_{EW} \), \( \langle \phi \rangle \neq 0 \)]:

\[ \Gamma(T < T_{EW}) \propto e^{-E_{sph}(T)/T} \]

[Arnold, McLerran-Khlebnikov, Shaposhnikov]

[Kuzmin, Rubakov, Shaposhnikov]
Baryogenesis in the Standard Model: rise and fall of electroweak baryogenesis

The order parameter of the electroweak phase transition is the Higgs vev:

- $T > T_{EW}, \langle \phi \rangle = 0$ unbroken phase
- $T < T_{EW}, \langle \phi \rangle \neq 0$ broken phase

If the phase transition is first order, the two phases coexist at $T = T_c$ and the phase transition proceeds via bubble nucleation.

Sphalerons are in equilibrium outside the bubbles, and out of equilibrium inside the bubbles (rate exponentially suppressed by $E_{\text{sph}}(T) / T$)

CP-violating interactions in the wall together with unsuppressed sphalerons outside the bubble generate a $B$ asymmetry which diffuses into the bubble.

[Cohen, Kaplan, Nelson]
For the mechanism to work, sphalerons must be suppressed inside the bubbles (otherwise erase the generated B+L asymmetry)

\[ \Gamma(T < T_{EW}) \propto e^{-E_{sp}(T)/T} \text{ with } E_{sp}(T) \approx (8\pi/g) \langle \phi(T) \rangle \]

The out-of-equilibrium condition is

\[ \frac{\langle \phi(T_c) \rangle}{T_c} \gtrsim 1 \]

\[ \Rightarrow \text{ strongly first order phase transition required} \]

To determine whether this is indeed the case, study the 1-loop effective potential at finite temperature. The out-of-equilibrium condition \[ \Phi(T_c)/T_c > 1 \] then translates into:

\[ m_H \lesssim 40 \text{ GeV} \quad \text{condition for a strongly first order transition} \]

\[ \Rightarrow (\text{standard) electroweak baryogenesis excluded by LEP} \]

(well before the LHC)

Also not enough CP violation in the Standard Model
The observed baryon asymmetry requires new physics beyond the Standard Model

⇒ 2 approaches:

1) modify the dynamics of the electroweak phase transition [+ new source of CP violation needed]

MSSM with a light top squark, 2 Higgs doublet model...

2) generate a B-L asymmetry at $T > T_{\text{EW}}$, which is then converted into a B asymmetry by sphaleron processes

out-of-equilibrium decays of heavy gauge bosons (= GUT baryogenesis, however conflict with inflation) or of heavy states coupling to the neutrinos (leptogenesis), ...
The observation of neutrino oscillations from different sources (solar, atmospheric and accelerator/reactor neutrinos) has led to a well-established picture in which neutrinos have tiny masses and can change flavour (e.g. \( \nu_e \rightarrow \nu_\mu / \nu_\tau \)) as they propagate through matter.

A link with neutrino masses: Baryogenesis via leptogenesis

![Graph](image)

**FIG. 5:** Ratio of the observed \( \bar{\nu}_e \) spectrum to the expectation for no-oscillation versus \( L_0/E \) for the KamLAND data. \( L_0 = 180 \) km is the flux-weighted average reactor baseline. The 3-\( \nu \) histogram is the best-fit survival probability curve from the three-flavor unbinned maximum-likelihood analysis using only the KamLAND data.

Disparition of reactor \( \bar{\nu}_e \) in the KamLAND experiment due to their oscillations into \( \bar{\nu}_\mu \) and \( \bar{\nu}_\tau \)

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
\]
The tiny neutrino masses can be interpreted in terms of a high scale:

\[ m_\nu = \frac{v_{EW}^2}{M} \quad M \sim 10^{14} \text{ GeV} \]

Several mechanisms can realize this mass suppression. The most popular one (type I seesaw mechanism) involves heavy Majorana neutrinos:

![Diagram](image)

Interestingly, this mechanism contains all required ingredient for baryogenesis: out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry (L violation replaces B violation and is due to the Majorana masses) if their couplings to SM leptons violate CP

Fukugita - Yanagida
**CP violation:** being Majorana, the heavy neutrinos are their own antiparticles and can decay both into $l^+$ and into $l^-$

The decay rates into $l^+$ and into $l^-$ differ due to quantum corrections

\[ \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^*) \]

\[ \Rightarrow \text{asymmetry between lepton and antilepton abundances, which is partially washed out by } L\text{-violating processes and converted into a baryon asymmetry by the sphalerons} \]
The final baryon asymmetry can be expressed as:

$$Y_B = -0.42 \ C \ \frac{\eta \epsilon_{N_1}}{g^*} = -1.4 \times 10^{-3} \ \eta \epsilon_{N_1} \quad \text{(SM)}$$

$C = \text{conversion factor by sphaleron}$

$$<Y_B>_T = C \ <Y_{B-L}>_T$$

$$C' = \frac{8N_f + 4N_H}{22N_f + 13N_H} = \frac{28}{79} \quad \text{(SM)}$$

$g^* = \text{total number of relativistic dofs} \quad [g^* = 106.75 \text{ in the SM}]$

$\epsilon_{N_1} = \text{CP asymmetry in } N_1 \text{ decays}$

$\eta = \text{efficiency factor that takes into account the dilution of the lepton asymmetry by } L\text{-violating processes} \ (LH \rightarrow N_1, \ LH \rightleftharpoons \bar{L}H^* \cdots)$

$\rightarrow \text{must be determined by solving Boltzmann equations}$

baryogenesis via leptogenesis
Leptogenesis can explain the observed baryon asymmetry:

\[ M_1 \geq (0.5 - 2.5) \times 10^9 \text{ GeV} \]
depending on the initial conditions

[Davidson, Ibarra]

\[ \tilde{m}_1 \equiv (YY^\dagger)_{11} v^2 / M_1 \]
SO(10) Grand Unified Theories (GUTs) = natural framework for heavy Majorana neutrinos:

\[ SO(10) \supset SU(3)_C \times SU(2)_L \times U(1)_Y \]

(i) \(16 = (Q, \bar{u}, \bar{d}, L, \bar{e}) \oplus \bar{N}\)

(ii) B-L is a generator of SO(10) \(\Rightarrow\) the mass scale of the \(N_R\) is associated with the breaking of the gauge group \(\Rightarrow M_R >> M_{\text{weak}}\) natural

\[
\begin{align*}
M_1 : M_2 : M_3 &\sim m_u^2 : m_c^2 : m_t^2, \quad \text{with } M_1 \sim 10^5 \text{ GeV} \\
&\rightarrow \text{incompatible with successful leptogenesis}
\end{align*}
\]
However, in SO(10) models with an underlying left-right symmetry, neutrino masses also receive contributions from an heavy SU(2)L triplet:

\[ \Delta_L = \text{SU}(2)_L \text{ triplet with couplings } f_{\alpha\beta} \text{ to the leptons } L_\alpha \]

The SU(2)_L triplet also contributes to leptogenesis. If \( M_1 \ll M_\Delta \), it mainly affects leptogenesis by contributing to the CP asymmetry in \( N_1 \) decays:

The heavy neutrino masses and the triplet couplings to leptons are determined by the same matrix \( f \). Possible to reconstruct the \( f_{\alpha\beta} \) from low-energy data (neutrino masses and mixing angles) with minimal assumptions on the \( N_i \) couplings \( \Rightarrow 8 \) solutions, some of which lead to successful leptogenesis

[Hambye, Senjanovic]

[Hosteins, SL, Savoy (2006)]
• flavour-dependent Boltzmann equations (independent evolution of the lepton asymmetry in the e, μ and τ flavours)
• contribution of N2
• corrections to Md = Me from non-renormalizable operators
• flavour-dependent “N2 leptogenesis” in the solutions with a light N1: N2 decays generate an asymmetry in a flavour that is only mildly washed out by N1 inverse decays

\[ \mathcal{V}_R = (B-L)\text{-breaking scale} \]
Inputs: normal hierarchy with $m_1 = 10^{-3}$ eV, $\theta_{13} = 0$, $\delta = 0$, different choices of Majorana and high-energy phases – $v^2 = 0.1 \, v_L \, v_R - T_{in} = 10^{11}$ GeV

Successful leptogenesis possible for a (B-L)-breaking scale $v_R \gtrsim 10^{13}$ GeV

[Abada, Hosteins, Josse-Michaux, SL (2008)]
Successful leptogenesis possible for $v_R \sim (10^{13} - 10^{14})$ GeV

[Abada, Hosteins, Josse-Michaux, SL (2008)]
In spite of a huge enhancement by lepton flavour effects, the baryon asymmetry generated from N2 decays fails to reproduce the observed value (no successful set of parameters found)

[Abada, Hosteins, Josse-Michaux, SL (2008)]
Impact of lepton flavour effects

Quantitative difference between the solution of the flavour-dependent Boltzmann equations (independent evolution of the lepton asymmetry in the e, μ and τ flavours) and the 1-flavour approximation.

Particularly strong impact when N\textsubscript{2} decays generate an asymmetry in a lepton flavour that is only mildly washed out by N\textsubscript{1} inverse decays.
A predictive scheme for leptogenesis

Another class of SO(10) models leads to pure triplet seesaw mechanism \(\Rightarrow\) neutrinos masses proportional to triplet couplings to leptons:

\[
(M_\nu)_{\alpha\beta} = \frac{\lambda_H f_{\alpha\beta}}{2M_\Delta} v^2
\]

These models contain heavy (non-standard) leptons that induce a CP asymmetry in the heavy triplet decays

The SM and heavy lepton couplings are related by the SO(10) gauge symmetry, implying that the CP asymmetry can be expressed in terms of (measurable) neutrino parameters

[Frigerio, Hosteins, SL, Romanino (2008)]
Dependence on the light neutrino parameters

\[ \epsilon_\Delta \propto \frac{1}{(\sum_i m_i^2)^2} \left\{ c_{13}^4 c_{12}^2 s_{12}^2 \sin(2\rho) m_1 m_2 \Delta m_{21}^2 \
+ c_{13}^2 s_{13}^2 c_{12}^2 \sin(2(\rho - \sigma)) m_1 m_3 \Delta m_{31}^2 
- c_{13}^2 s_{13}^2 s_{12}^2 \sin(2\sigma) m_2 m_3 \Delta m_{32}^2 \right\} \]

\[ U_{ei} = (c_{13} c_{12} e^{i\rho}, c_{13} s_{12}, s_{13} e^{i\sigma}) \]

→ \( \epsilon_\Delta \) depends on measurable neutrino parameters

→ the CP violation needed for leptogenesis is provided by the CP-violating phases of the lepton mixing matrix (the Majorana phases to which neutrinoless double beta decay is sensitive)

An approximate solution of the Boltzmann equations suggested that successful leptogenesis is possible if the "reactor" mixing angle \( \theta_{13} \) is large enough (prior to its measurement by the Daya Bay experiment) [Frigerio, Hosteins, SL, Romanino (2008)]

→ confirmed by the numerical resolution of the flavour-dependent Boltzmann equations [SL, B. Schmauch, in progress]
Parameter space allowed by successful leptogenesis

$M_\Delta$ (GeV)

$m_1$ (eV)

isocontours of $\eta$

[SL, B. Schmauch (in progress)]
**isocontours of $\eta$**

\[ \sin^2 \theta_{13} \]

\[ m_1 \text{ (eV)} \]

[SL, B. Schmauch (in progress)]
$M_\Delta \ (\text{GeV})$

$|m_{\beta\beta}| \ (\text{eV})$

isocontours of $\eta$

[SL, B. Schmauch (in progress)]
Conclusions

The observed baryon asymmetry of the Universe cannot be generated by standard electroweak baryogenesis, the only available mechanism within the Standard Model, and requires new physics.

An attractive possibility is leptogenesis. Neutrino masses and the baryon asymmetry share a common origin, but this scenario cannot be directly tested (at least in its standard version).

Successful leptogenesis is compatible with Grand Unification, e.g.:

- SO(10) models with a left-right symmetric seesaw mechanism involving both heavy Majorana neutrinos and an electroweak triplet
- SO(10) models with pure triplet seesaw ⇒ predictive leptogenesis
Although difficult to test, leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \rightarrow (A,Z+2) \, e^- \, e^-$ [proof of the Majorana nature of neutrinos - necessary condition]

- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [neither sufficient nor necessary though]

- experimental exclusion of non-standard electroweak baryogenesis scenarios [e.g. MSSM with a light stop]