Electromagnetic Leptogenesis

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March 12, 2009
The Challenge

The universe contains baryons, but essentially no antibaryons.

\[ \frac{n_B}{n_\gamma} = 6 \times 10^{-10} ; \quad \frac{n_B}{n_B} \ll 1 \]

Standard cosmology: Any initial baryon - antibaryon asymmetry would have been erased.

How did \[ n_B = n_B \quad \Rightarrow \quad n_B \gg n_B \] ?
Sakharov $n_B = n_{\bar{B}} \quad \rightarrow \quad n_B \gg n_{\bar{B}}$

requires CP.

The CP in the quark mixing matrix, seen in B and K decays, leads to much too small a $B-\bar{B}$ asymmetry.

If quark CP cannot generate the observed $B-\bar{B}$ asymmetry, can some scenario involving leptons do it?

The candidate scenario: Leptogenesis.
Leptogenesis—The General Idea

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

The See-Saw Mechanism

The very heavy neutrinos $N$ would have been made in the hot Big Bang.

Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski
Leptogenesis — Step 1

The heavy neutrinos $N$, like the light ones $\nu$, are Majorana particles. Thus, an $N$ can decay into $l^-$ or $l^+$. 

*If $\nu$ oscillation violates CP, then quite likely so does $N$ decay. In the See-Saw, these two CP violations have a common origin: One Yukawa coupling matrix, $y$.*

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow l^- + \varphi^+ \quad \text{and} \quad N \rightarrow l^+ + \varphi^-$$

This produces a universe with unequal numbers of *leptons and antileptons.*
Leptogenesis — Step 2

The Standard-Model *Sphaleron* process, which does not conserve Baryon Number $B$, or Lepton Number $L$, but does conserve $B - L$, acts.

\[
\begin{align*}
B_i &= 0 \\
L_i &
eq 0
\end{align*}
\]

\[
\begin{align*}
B_f &\approx -\frac{1}{3}L_i \\
L_f &\approx \frac{2}{3}L_i \approx -2B_f
\end{align*}
\]

*Initial state from $N$ decays*  
*Final state*

*There is now a Baryon Asymmetry.*
Leptogenesis In Greater Depth

The see-saw model adds to the Standard Model —

\[ L_{\text{new}} = - \sum_{k=1}^{3} \frac{M_k}{2} N_{kR}^c N_{kR} - \sum_{j,k=1}^{3} y_{jk} \left[ \nu_{jL} \phi^0 - \ell_{jL} \phi^- \right] N_{kR} + h.c. \]

The Yukawa couplings \( y_{jk} \) cause —

\[ N_k \rightarrow \ell_j^+ + \phi^\pm \quad \text{and} \quad N_k \rightarrow (\nu_j^0 + \phi^0) . \]
\[ \text{CP In N Decay} \]

All CP-violating phases must come from the Yukawa coupling matrix \( y \).

Tree–loop interferences lead to CP. Example:

\[ \Gamma(N_1 \rightarrow \ell_j^- + \phi^+) - \Gamma(N_1 \rightarrow \ell_j^+ + \phi^-) \propto \text{Im}(y_{j1}^* y_{n1}^* y_{j2} y_{n2}) \]
Simplest picture:

The leptonic asymmetry comes from decay of the lightest $N, N_1$, and the final lepton flavors, $e, \mu, \tau$, may be treated identically.

Then, summing over the final lepton flavors, the $\mathcal{CP}$ asymmetry is —

$$\varepsilon \equiv \frac{\Gamma(N_1 \rightarrow L\phi) - \Gamma(N_1 \rightarrow \bar{L}\phi)}{\Gamma(N_1 \rightarrow L\phi) + \Gamma(N_1 \rightarrow \bar{L}\phi)}$$

$$= \frac{1}{8\pi} \frac{1}{(y^+ y)_1} \sum_m \Im \left\{ \left( y^+ y \right)_1 m \right\}^2 \left[ \frac{M_2^2}{M_1^2} \right] K$$

$$\varepsilon \sim y^2/10$$

To explain $n_B/n_\gamma \sim 10^{-9}$ requires $\varepsilon \sim 10^{-6}$. 
The N Masses Required
For Leptogenesis

After the EW phase transition (which is after the $N_k$ have decayed), $\langle \phi^0 \rangle_0 \equiv v \cong 250$ GeV. Then —

$$\bar{\nu}_L y \phi^0 N_R \rightarrow \bar{\nu}_L (y v) N_R = \bar{\nu}_L M_D N_R$$

In the see-saw picture, where the N masses are $>> M_D$, the light $\nu$ masses $M_\nu$ are —

$$M_\nu \sim M_D^2/M_N \sim (y v)^2/M_N \sim 10^{-1} \text{eV}.$$
$M_v \sim M_D^2/M_N \sim (y\nu)^2/M_N \sim 10^{-1}\text{eV}.$

For leptogenesis, we required that —

$$\varepsilon \sim y^2/10 \sim 10^{-6}$$

Together, these requirements imply that —

$$M_N \sim 10^9 \text{GeV}.$$

*Leptogenesis requires very heavy neutrinos, far beyond the range of LHC.*
Leptogenesis and $\mathcal{CP}$
In Light $\nu$ Oscillation

In a basis where the charged-lepton mass matrix is diagonal, our Yukawa coupling matrix $y$ is the only source of CP violation among the leptons.

Though $M_D$, the CP phases in $y$ feed into the leptonic mixing matrix $U$.

Through $U$, these phases lead to CP in light neutrino oscillation.
Electromagnetic Leptogenesis

(Nicole Bell, B.K., Sandy Law)

Suppose new physics at a high mass scale $\Lambda > M_N$ leads to the electromagnetic $N$ decay mode —

$N \rightarrow \nu + \gamma$  Toy Model

or the mode —

$N \rightarrow L + \varphi + (\gamma \text{ or } Z \text{ or } W)$

More realistic; respects SM conservation laws

Emitted in standard leptogenesis
Q: Could $\mathcal{CP}$ in such decays be a successful alternative to the standard leptogenesis scenario?

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

The $N \rightarrow \nu + \gamma$ Toy Model

Transition magnetic and electric dipole moments
No CP In Any Decays
In Lowest Order

Tree-level interference between an Electric DM and a Magnetic DM cannot lead to —

\[ \Gamma(N_k \rightarrow \nu_j + \gamma) \neq \Gamma(N_k \rightarrow \bar{\nu}_j + \gamma) . \]

There can never be a difference between the rates for CP-conjugate decay modes in first order in the Hamiltonian.
If $T \equiv i(S - I)$ is the transition operator for the decay $Q \rightarrow a_1 + a_2 + \ldots$,

CPT – invariance

$$\left| \langle a_1(p_1, \lambda_1)a_2(p_2, \lambda_2)\ldots |T| Q(J_z) \rangle \right|^2$$

$$= \left| \langle \bar{a}_1(p_1, -\lambda_1)\bar{a}_2(p_2, -\lambda_2)\ldots |T^\dagger| \bar{Q}(-J_z) \rangle \right|^2$$

Helicity

Spin projection

To first order in the Hamiltonian $H$, $T = H$. Then $T^\dagger = T$.

Then —

$$\Gamma(Q \rightarrow a_1 + a_2 + \ldots) = \Gamma(\bar{Q} \rightarrow \bar{a}_1 + \bar{a}_2 + \ldots)$$
In the $N \rightarrow \nu + \gamma$ Toy Model From Tree – Loop Interference

The assumed effective EM coupling of the neutrinos is:

$$-L_{EM-\text{Toy}} = \frac{1}{\Lambda} \sum_{j,k=1}^{3} \nu_j \sigma^{\alpha\beta} \lambda_{jk} N_{kR} F_{\alpha\beta} + h.c.$$
An example of tree-loop interference:

\[
\Gamma(N_k \rightarrow \nu_j + \gamma) - \Gamma(N_k \rightarrow \bar{\nu}_j + \gamma) \propto \Im \left( \lambda_{jk}^* \lambda_{nk}^* \lambda_{nm} \lambda_{jm} \right)
\]

This model leads to a $\mathcal{C}\mathcal{P}$ asymmetry $\varepsilon$ rather similar to the one from standard leptogenesis, with $y \Rightarrow \lambda$.

The $\mathcal{C}\mathcal{P}$ phases are now in $\lambda$.

*EM leptogenesis can succeed.*
In the 
\[ N \rightarrow L + \phi + (\gamma \text{ or } Z \text{ or } W) \] Model

From Tree – Loop Interference

The effective “EM” interaction is now —

\[-L^{"EM"} = \frac{1}{\Lambda^2} \sum_{j,k=1}^{3} L_{jL} \sigma^{\alpha\beta} \left[ \lambda'_{jk} B_{\alpha\beta} + \tilde{\lambda}'_{jk} \tau \cdot W_{\alpha\beta} \right] \rho N_{kR} + h.c.\]

Lepton doublet

Higgs doublet

\( I_W = 0 \) gauge field

\( I_W = 1 \) gauge field

This \( \rightarrow \) \( N \) decays such as \( N \rightarrow l^- + \phi^0 + W^+ \)
An example of tree-loop interference:

\[ \begin{align*}
N_k & \rightarrow \phi \rightarrow \ell_j + \left( N_k \rightarrow \phi, \phi^\dagger \rightarrow \ell_n, \ell_n, \phi \rightarrow \ell_j \right) \rightarrow B_\alpha \\
\end{align*} \]

This interference and its toy model counterpart lead to CP asymmetries \( \varepsilon \) related by —

\[
|\varepsilon'_{\text{EM}}(\lambda')| = \left( \frac{M_k}{8 \pi \Lambda} \right)^2 |\varepsilon_{\text{Toy-Model}}(\lambda)|.
\]

Apart from the suppression factor, the “EM” and toy models give similar asymmetries. Hence, the “EM” model and standard leptogenesis give similar asymmetries.
The New EM Physics and the Masses of the Light Neutrinos

Once $\langle \phi^0 \rangle_0 \neq 0$, L" EM" leads to —

Dirac mass, leading to Majorana mass $m_{\nu}^A$

Majorana mass $m_{\nu}^B$

*EM leptogenesis and the light $\nu$ masses are connected.*
# A Comparison

<table>
<thead>
<tr>
<th>Standard</th>
<th>Electromagnetic</th>
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<tbody>
<tr>
<td>$\Gamma_1 = \frac{1}{8\pi} (y^+ y)_{11} M_1$</td>
<td>$\Gamma_1 = \frac{1}{2\pi} \left( \lambda'^+ \lambda' \right)_{11} M_1 \left( \frac{M_1^2}{8\pi\Lambda^2} \right)^2$</td>
</tr>
<tr>
<td>$\varepsilon \sim \frac{1}{8\pi} \frac{\Im m(y^+ y)<em>{1m}^2}{(y^+ y)</em>{11}} \frac{M_1}{M_m}$</td>
<td>$\varepsilon \sim \frac{1}{2\pi} \frac{\Im m(\lambda'^+ \lambda')<em>{1m}^2}{(\lambda'^+ \lambda')</em>{11}} \frac{M_1}{M_m} \left( \frac{M_1^2}{8\pi\Lambda^2} \right)^2$</td>
</tr>
<tr>
<td>$m_\nu \sim y^T M_N^{-1} y \langle \phi \rangle^2$</td>
<td>$m_\nu^A \sim \lambda'^T M_N^{-1} \lambda' \langle \phi \rangle^2 \left( \frac{g'}{16\pi^2} \right)^2$</td>
</tr>
<tr>
<td></td>
<td>$m_\nu^B \sim \frac{\lambda'^T M_N \lambda'}{\Lambda^2} \langle \phi \rangle^2 \frac{1}{16\pi^2}$</td>
</tr>
</tbody>
</table>
A Specific Example

Suppose the new “EM” interactions dominate over the Yukawa interactions of standard leptogenesis.

Disregarding matrix structure,

\[ \Lambda \sim 10M_2 \sim 20M_1 \text{ and } \lambda' \sim 35 \text{ gives } \varepsilon \sim 10^{-6}. \]

With these parameters, \( m^B \) dominates the light neutrino masses, whose value, \( \sim 0.1 \text{ eV} \), requires that —

\[ M_1 \sim 10^{13} \text{ GeV}. \]

Like standard leptogenesis, EM leptogenesis requires that the heavy neutrinos \( \mathbf{N} \) be far above the LHC range.
Our Two Questions

Q: Could $\mathcal{CP}$ in EM decays be a successful alternative to the standard leptogenesis scenario?

A: Yes.

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

A: No.
The Link Between the Baryon Asymmetry and Light $\nu$ CP

In standard leptogenesis, all leptonic CP comes from the Yukawa coupling matrix $y$.

CP in light $\nu$ oscillation and the CP that led to the Baryon Asymmetry are linked. One expects CP in both places or in neither.

In EM leptogenesis, leptonic CP has a different source — the new “EM” interactions.

But CP in light $\nu$ oscillation and the CP that led to the Baryon Asymmetry are still linked.
The new EM couplings lead to neutrino masses.

If leptogenesis is driven by these new couplings, then the neutrino masses probably are too.

CP-violating couplings will lead to CP-violating mass matrices, which in turn will lead to CP violation in oscillation.

*Experiments to look for CP in light \( \nu \) oscillation are very strongly motivated.*