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Electromagnetic Leptogenesis

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THE UNIVERSITY OF MELBOURNE

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<u>*Reference*</u>*:*

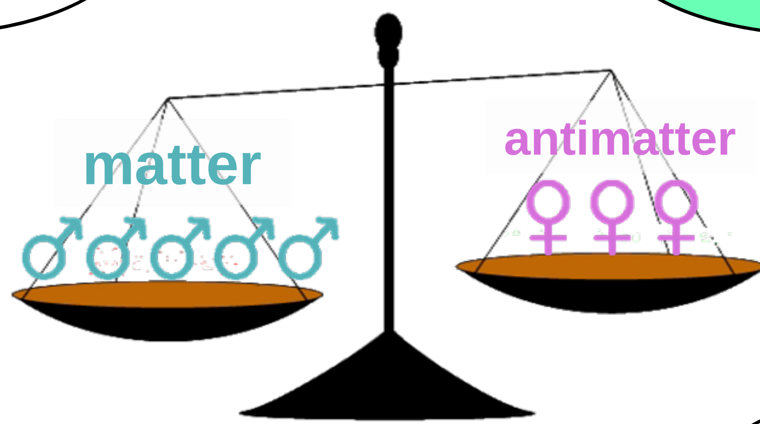
N. F. Bell et al. *Phys. Rev.* D78 (2008) 085024 (arXiv:0806.3307 [hep-ph])

The real issue: Matter is more dominant than Antimatter in our Universe

Electroweak Baryogenesis

Leptogenesis

Affleck-Dine



GUT Baryogenesis

Our Universe

Spontaneous Baryogenesis

models with extra-dimensions

The size of this asymmetry is normally represented by the **baryon-to-photon** ratio which can be measured experimentally: $\eta_B^{\rm CMB} = (6.3 \pm 0.3) \times 10^{-10}$.

So, we need **a model of Baryogenesis**

Prelude to Leptogenesis

While there are many ways to extend the Standard Model (SM) to solve the baryogenesis problem, the need to explain **neutrino masses** motivates a path via the lepton sector.

A popular way to generate neutrino mass is via the (type I) *seesaw mechanism*, which requires:

Standard Model + **RH neutrinos (N_R)**

The corresponding neutrino interaction Lagrangian is

$$\mathcal{L}_{\rm int} = -\bar{\ell}_L\, h\, \phi\, N_R - \frac{1}{2}\, \overline{N_R^c}\, M\, N_R + {\rm h.c.}$$

For the case of three additional N_R's, one then gets six neutrino Majorana mass eigenstates

- three *light* states (ν) with mass: $m_\nu \simeq \mathcal{O}\left(\langle\phi\rangle^2/M\right)$
- three *heavy* states (N) with mass: $M_N \simeq \mathcal{O}\left(M\right)$

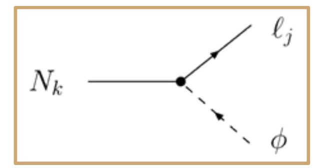
for $h\langle\phi\rangle \ll M$

Interestingly, the seesaw Lagrangian can also lead to leptogenesis in the early universe:

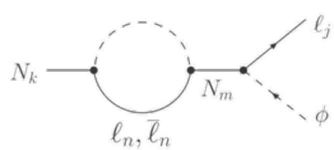
$$\mathcal{L}_{\rm int} = -\overline{\ell}_L\, h\, \phi\, N_R - \frac{1}{2}\,\overline{N_R^c}\, M\, N_R + \text{h.c.}$$

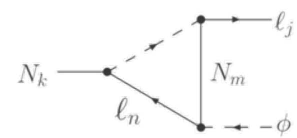
Because

- the **Yukawa** term can induce the ***L*-violating decay**:-



- such decay of the heavy RH neutrinos can **violate *CP*** at the loop level





- and when such process goes **out-of-equilibrium** due to the expansion of the universe, an excess in *L* can be created.

Subsequently, this excess in *L* will be partially converted into a baryon asymmetry via *electroweak sphaleron* processes.

Our aims and motivations

Given the previous setup (SM plus heavy RH neutrinos), it is perhaps natural to explore other ways which can **connect the ordinary leptons with the heavy neutrinos** besides the Yukawa couplings

$$\bar{\ell}_L \, h \, \phi \, N_R$$

If so, we would like to know

- whether such new interaction terms can provide a **viable alternative** for achieving successful leptogenesis;
- whether the resulting **leptogenesis scale** (≈ the mass scale of the heavy neutrinos) can be different from the standard version of $10^9 - 10^{13}$ GeV;
- its implications on the **link between the high- and low-energy** sectors in general (e.g. *CP* violation parameters, neutrino masses).

Electromagnetic dipole moment couplings

In this work, we are interested in exploring the **electromagnetic** (EM) couplings between the light and heavy neutrinos through *effective* operators of the form:

$$\frac{1}{\Lambda}\,\overline{\psi}_1\,\mu\,\sigma^{\alpha\beta}\psi_2\,F_{\alpha\beta}$$

magnetic dipole moment

$$\frac{i}{\Lambda}\,\overline{\psi}_1\,d\,\gamma^5\sigma^{\alpha\beta}\psi_2\,F_{\alpha\beta}$$

electric dipole moment

We assume that these are generated by some beyond the SM physics at energy above Λ.

μ , d are dimensionless couplings,

$F_{\alpha\beta}$ is the electromagnetic field strength tensor, and

Λ is the cutoff scale of our effective theory.

When written in terms of chiral fields, the most general dipole coupling of N_R to ν_L is given by

$$\frac{1}{\Lambda}\,\overline{\nu}_L\,\lambda\,\sigma^{\alpha\beta}N_R\,F_{\alpha\beta}\;, \qquad \lambda \equiv \mu + i\,d$$

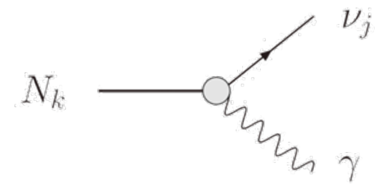
We will refer to this as the **electromagnetic dipole moment (EMDM)** operator.

For better illustration and comparison with standard leptogenesis, we begin by exploring the possibility of lepton asymmetry generation in a toy model where

Standard Model + **heavy Majorana neutrinos** + **dim-5 EMDM couplings**

$$-\frac{1}{\Lambda}\,\lambda_{jk}\,\overline{\nu}_{Lj}\,\sigma^{\alpha\beta}P_R\,N_k\,F_{\alpha\beta}$$

Through this dim-5 term, the heavy RH neutrinos can decay into a light neutrino and a photon in the early universe



The corresponding decay rate for such *L*-violating process (summed over final flavor *j*) is given by

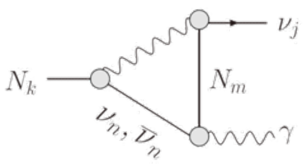
$$\Gamma_{(N_k\to\nu\,\gamma)} = \Gamma_{(N_k\to\overline{\nu}\,\gamma)} = \frac{(\lambda^\dagger\lambda)_{kk}}{4\pi}\,\frac{M_k^3}{\Lambda^2} \qquad k = 1,2,3.$$

An EM leptogenesis toy model (cont.)

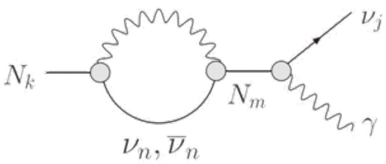
To ascertain whether leptogenesis is possible, the key quantity of interest is the *CP* asymmetry in the decays of *N*

$$\varepsilon^{(5)}_{\rm em} = \frac{\Gamma(N \to \nu\gamma) - \Gamma(\overline{N} \to \overline{\nu}\gamma)}{\Gamma(N \to \nu\gamma) + \Gamma(\overline{N} \to \overline{\nu}\gamma)}$$

Just like in standard leptogenesis, we expect the leading contribution to the *CP* asymmetry to come from the **interference** between the tree-level process and the 1-loop corrections with *on-shell* intermediate states:



vertex correction



self-energy correction

Through explicit computation, one finds that (in the limit of hierarchical RH neutrinos):

$$\varepsilon^{(5)}_{k,j}(z \gg 1) \simeq \frac{(M_k/\Lambda)^2}{2\pi(\lambda^\dagger\lambda)_{kk}} \sum_{m\neq k} {\rm Im}\left[\lambda^*_{jk}\lambda_{jm}\left\{\frac{2}{3\sqrt{z}}\,(\lambda^\dagger\lambda)_{km} + \frac{1}{z}\,(\lambda^\dagger\lambda)_{mk}\right\}\right]\,, \qquad z \equiv M_m^2/M_k^2$$

Since the complex coupling matrix λ is arbitrary, the *CP* parameter is in general *nonzero*, showing that *L* asymmetry generation is possible via the EMDM channel.

A more realistic EM leptogenesis model

The previous setup is simple and can help us easily visualize how EMDM like interactions provide a viable alternative for leptogenesis, it is however unrealistic as the dim-5 operators are *not* SM gauge invariant.

To construct an effective theory that is realistic, we only employ EMDM operators that are compatible with the SM. It turns out that the most economical of such terms are of **dim-6**.

Standard Model + **heavy Majorana neutrinos** + **dim-6 EMDM couplings**

$$-\frac{1}{\Lambda}\lambda_{jk}\,\overline{\nu}_{Lj}\,\sigma^{\alpha\beta}P_R\,N_k\,F_{\alpha\beta} \quad\Longrightarrow\quad \begin{cases} -\dfrac{1}{\Lambda^2}\,\overline{\ell}_j\,\lambda_{jk}\,\phi\,\sigma^{\alpha\beta}\,P_R\,N_k\,B_{\alpha\beta} \\ -\dfrac{1}{\Lambda^2}\,\overline{\ell}_j\,\widetilde{\lambda}_{jk}\,\phi\,\sigma^{\alpha\beta}\,P_R\,N_k\,\vec{\tau}\cdot\vec{W}_{\alpha\beta} \end{cases}$$

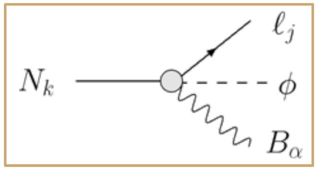
where ϕ is the **SM Higgs doublet**, $B_{\alpha\beta}$ and $W_{\alpha\beta}$ are the $U(1)_Y$ and $SU(2)_L$ field tensors. After spontaneous symmetry breaking, these operators will give rise to the required transition moments.

A more realistic EM leptogenesis model (cont.)

In the early universe, such dim-6 operators give rise to a **3-body** decay process for the heavy RH neutrino

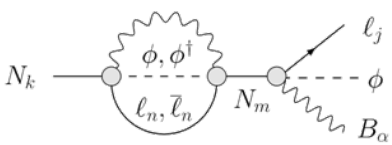
$$N_R \to \ell_L + \phi + (B_\mu \text{ or } W^i_\mu)$$

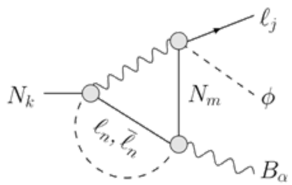
For simplicity, let's consider only one of the decay channels:-



$j = e, \mu, \tau.$
$k = 1, 2, 3.$

This decay **violates lepton number**, and it can be shown that it also **violates *CP*** in general, by analyzing the effects of high-order graphs such as:





Using similar methods as in the dim-5 case, one can derive some useful expressions for the relevant quantities. Although the mathematics in the dim-6 case is more complicated, it turns out that results are very much like before

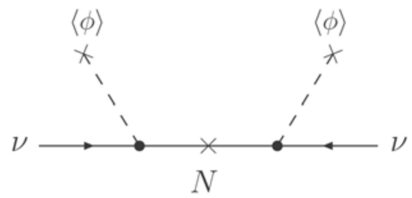
$$\Gamma_{(N_1 \to \ell\,\phi\,B_\alpha)} = \left(\frac{M_1}{8\pi\Lambda}\right)^2 \Gamma_{(N_1 \to \nu\,\gamma)} \qquad ; \qquad |\varepsilon_1^{(6)}| \simeq \left(\frac{M_1}{8\pi\Lambda}\right)^2 |\varepsilon_1^{(5)}|$$

Hence in principle, successful leptogenesis is possible in this model.

Implications for light neutrino masses

Recall from standard leptogenesis with Yukawa couplings that light neutrino masses can be generated by the **Type I seesaw** mechanism:

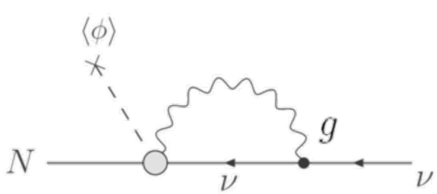
a realisation of the seesaw mass term is given by



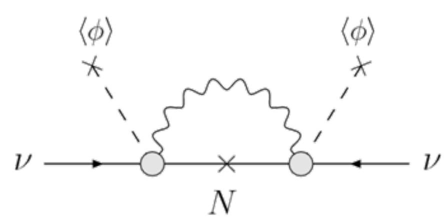
$$m_\nu \simeq \frac{h^2 \langle \phi \rangle^2}{M}$$

Here we note that the connection to leptogenesis comes from the **Yukawa coupling *h*** which also controls the N_R decay rate, as well as the *CP* parameter.

In **electromagnetic leptogenesis**, although in principle the Yukawa term can be removed (hence, no neutrino mass at the lowest order), *radiative corrections* involving the EMDM operators can however induce contributions to the neutrino mass terms after spontaneous symmetry breaking:



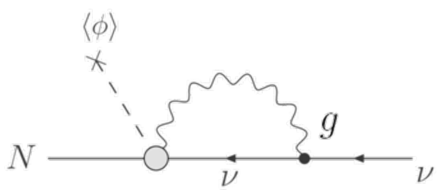
contribution to neutrino Dirac mass



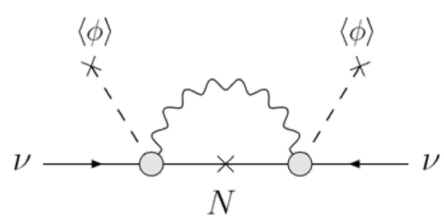
contribution to light neutrino Majorana mass

Implications for light neutrino masses (cont.)

Since we do not specify the UV completion of the theory, we estimate the contributions to neutrino mass using naïve dimensional analysis.



$$m_D \simeq \frac{\lambda g \langle\phi\rangle}{16\pi^2}$$



$$m_\nu \simeq \frac{\lambda^2 \langle\phi\rangle^2}{M} \left(\frac{M}{4\pi\Lambda}\right)^2$$

One can then apply Type I seesaw on the induced m_D to get:

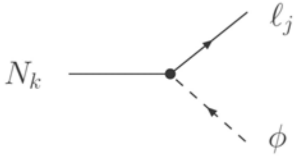
$$m_\nu \simeq m_D\, M^{-1}\, m_D^T \quad \Rightarrow \quad m_\nu \simeq \frac{\lambda^2 \langle\phi\rangle^2}{M} \left(\frac{g}{16\pi^2}\right)^2$$

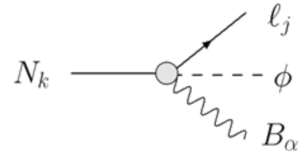
So, the role previously played by coupling h is now simply replaced by λ, which means that there will *still* be a strong connection between light neutrino parameters and leptogenesis.

The comparison of key quantities in the two scenarios (for $k = 1$ and summing over j) assuming a hierarchical RH neutrino mass spectrum:

$$\bar{\ell}_L \, h \, \phi \, N_R$$

Yukawa





$$\frac{1}{\Lambda^2} \, \bar{\ell}_L \, \lambda \, \phi \, \sigma^{\alpha\beta} N_R \, B_{\alpha\beta}$$

Electromagnetic

Yukawa:

$$\Gamma_1 = \frac{(h^\dagger h)_{11} \, M_1}{16\pi}$$

$$|\varepsilon| \simeq \sum_{m \neq 1} \frac{\mathrm{Im}[(h^\dagger h)^2_{1m}]}{\pi \, (h^\dagger h)_{11}} \frac{M_1}{M_m}$$

$$m_\nu \simeq \frac{h^2 \langle \phi \rangle^2}{M}$$

Electromagnetic:

$$\Gamma_1 = \frac{(\lambda^\dagger \lambda)_{11} \, M_1}{4\pi} \left(\frac{M_1^2}{8\pi \, \Lambda^2} \right)^2$$

$$|\varepsilon| \simeq \sum_{m \neq 1} \frac{\mathrm{Im}[(\lambda^\dagger \lambda)^2_{1m}]}{\pi \, (\lambda^\dagger \lambda)_{11}} \frac{M_1}{M_m} \left(\frac{M_1^2}{8\pi \, \Lambda^2} \right)^2$$

$$m_\nu \simeq \frac{\lambda^2 \langle \phi \rangle^2}{M} \left[\left(\frac{g}{16\pi^2} \right)^2 + \left(\frac{M}{4\pi\Lambda} \right)^2 \right]$$

Similarity between the two is clearly evident.

The leptogenesis parameter space

Given that the key equations in EM leptogenesis are in the same form as those in the standard case, it is sensible to assume that their dependence on the parameter space would also be largely similar.

Thus, it is convenient to draw upon many of the established results from standard leptogenesis.

We consider the scenario where the RH neutrino mass spectrum is hierarchical, then the asymmetry produced is predominantly due to the decay of the *lightest* RH neutrinos, N_1.

The final baryon asymmetry may be written as a product of three factors:

$$\eta_B \simeq d \; \varepsilon \; \kappa = \mathcal{O}(10^{-10})$$

d a global **dilution** factor which encapsulates the effects of **photon production**, the number of **relativistic degrees of freedom**, and the partial **conversion of L into B** via electroweak sphalerons. $\mathcal{O}(10^{-2})$

The leptogenesis parameter space (cont.)

ε

the raw ***CP* asymmetry** which is obtained from explicitly calculating the relevant loop diagrams. This quantity can be highly dependent on the neutrino model employed.

Assuming hierarchical *light* neutrinos, a ballpark estimate of this can be obtained [Davidson & Ibarra]:

$$|\varepsilon_1|^{\max} \approx 10^{-6}\left(\frac{M_1}{10^{10}\ \mathrm{GeV}}\right)$$

So, for the typical leptogenesis scale of $M_1 \geq 10^{10}$ GeV, the size of $|\varepsilon| \sim 10^{-6}$.

$\mathcal{O}(10^{-6})$

κ

the **efficiency factor** for L production obtained from studying the non-equilibrium evolution of the particle species using *Boltzmann equations*. It takes into account of the interplay between $\mathbf{N_1}$ **production** and L-asymmetry **washout processes** during the leptogenesis era.

It is dependent of the *decay parameter*:-

$$K_1 \equiv \frac{\Gamma(N_1 \to \ell\phi)}{H(T = M_1)}$$

For $M_1 \sim 10^{10}$ to 10^{14} GeV and K_1 in the range of **0.1 to 10**, the efficiency factor for many typical setups is about 10^{-1} to 10^{-2}. [Buchmüller et al.]

$\mathcal{O}(10^{-2})$

The EM leptogenesis scenario

By taking

$$d \simeq \mathcal{O}(10^{-2}) \qquad \varepsilon \simeq \mathcal{O}(10^{-6}) \qquad \kappa \simeq \mathcal{O}(10^{-2})$$

as the rough criteria for successful baryogenesis via leptogenesis, we can make some general observations for the EM leptogenesis scenario.

Suppose light neutrinos have $m_\nu \sim 10^{-2}$ eV and ignoring the matrix structure of coupling λ, we find

$$|\varepsilon^{\rm EM}| \sim 10^{-6} \beta_\Lambda^4 \left(\frac{M_1}{10^9 \ {\rm GeV}} \right) , \qquad \beta_\Lambda \equiv \frac{M_1}{\Lambda}$$

From this we see that

- the EM leptogenesis scale must be **greater than 10^9** GeV, as in the standard case;
- the presence of factor β_Λ implies that the RH neutrino mass hierarchy should *not* be too strong.

The EM leptogenesis scenario (an example)

A workable set of inputs for EM leptogenesis:

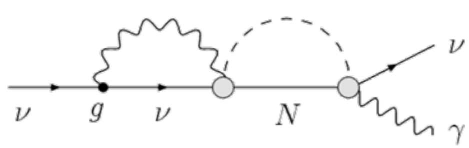
- selecting a moderate hierarchy of RH neutrinos $\Lambda \simeq 10 M_{2,3} \simeq 20 M_1$
- with EMDM couplings of order $\lambda \simeq \mathcal{O}(10)$
- setting $M_1 \simeq 5 \times 10^{12}$ GeV → $K_1 \approx 0.3$

can ensure $\varepsilon \simeq \mathcal{O}(10^{-6})$

moderate washout $\kappa \simeq \mathcal{O}(10^{-2})$

Some consequences of these parameters:

- implications for light neutrino masses $m_\nu^{(1)} \simeq 4 \times 10^{-2}$ eV , $m_\nu^{(2)} \simeq 1 \times 10^{-1}$ eV
- induced **light neutrino dipole moments** via 2-loops diagrams



→ $\mu_\nu^{\mathrm{eff}} \sim 5 \times 10^{-19}\, \mu_B$

which is much less than $\mathbf{10^{-11}\mu_B}$ from experiments and astrophysical bounds [Raffelt, Beacom et. al., Borexino, Texono collaborations] .

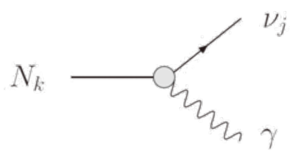
We believe leptogenesis is an elegant solution to the baryogenesis problem where the decay of the RH neutrinos provides the source of asymmetry generation.

Such decays are normally induced through the Yukawa couplings $\overline{\ell}_L \, h \, \phi \, N_R$ which also give rise to light neutrino masses.

In this work, we've looked beyond the minimal Yukawa interactions and investigated the **electromagnetic dipole moment** coupling between the light and heavy neutrinos (without introducing more new particles to the SM)

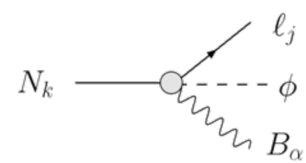
dim-5 model

$$-\frac{1}{\Lambda} \lambda_{jk} \, \overline{\nu}_{Lj} \, \sigma^{\alpha\beta} P_R \, N_k \, F_{\alpha\beta}$$



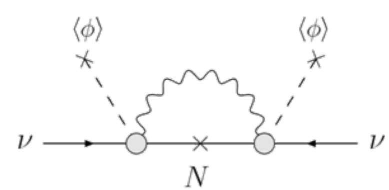
dim-6 model

$$-\frac{1}{\Lambda^2} \overline{\ell}_j \, \lambda_{jk} \, \phi \, \sigma^{\alpha\beta} P_R \, N_k \, B_{\alpha\beta}$$



But only the **dim-6 model** is compatible with the SM gauge symmetries.

Since the dim-6 EMDM term contains the **SM Higgs**, after spontaneous symmetry breaking, it can induce light neutrino masses radiatively:



Summary and Conclusions (cont.)

Overall, we can conclude that EM leptogenesis

- is in principle a **viable alternative** for achieving successful leptogenesis;
- requires the RH neutrino mass scale to be much **above 10^9 GeV**, somewhat akin to the standard version;
- but unlike the standard case, it does *not* favor a very strong hierarchy for the RH neutrino mass spectrum;
- maintains the **strong link between high- and low-energy** sectors (via EMDM coupling λ), i.e.

CP-violating phases in high-energy sector	↔	*CP*-violating mass matrices	↔	*CP* violation in ν oscillations

hence, looking for *CP* violation in light neutrino oscillation experiments is strongly motivated.

Thank You !!

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