Leptogenesis

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INT, 7/99

Aim: to explain

baryogenesis

$$\eta = \frac{n_B}{s} \simeq 0.6 - 1 \times 10^{-10}$$

required in nucleosynthesis

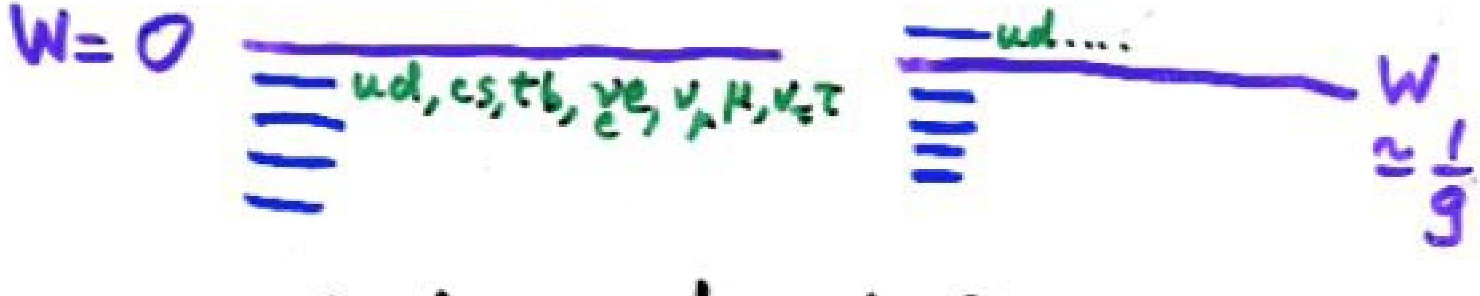
(and for our existence!)

Several Candidates,

but first an interlude

Sketch of B+L violation by Strong W fields

Strong W fields distort the normal Dirac sea structure, causing fermions charged under $SU(2)_{wk}$ to go in and out of the positive energy region



and go back for W reversed

But during phase transition, energy has other avenues (bubble formation, etc)

So can be left with net $B+L$.

<u>Salient fact</u>: fluctuations above T_{EW} wipe out any pre-existing $B+L$

(A) Out-of-equilibrium **decays** of **GUT leptoquarks**

Problem: too heavy to be regenerated after inflation

(B) **Sphaleron processes** before and during EW phase transition – strong ($O(\frac{1}{g})$) EW fields violate B+L, preserve B−L

Problem: required η achieved only for small m_H (< 70 GeV) or small $m_{\tilde{t}}$.

(c) <u>Affleck - Dine mechanism</u> - generation of B during evolution of classical squark field to equilib. value (zero)

$n_B \sim \dot{\phi}$. Problem: complicated interplay with inflaton dynamics; no B-L asymmetry → reheat must be $< T_{EW}$

(D) <u>Murayama - Yanagida Moroi variant</u>: Leptogenesis via evolution of classical sneutrino/higgs field Generates B-L, so can have $T_{RH} > T_{EW}$. Still some complex interplay w/ inflation dynamics.

(E) Out of equilibrium decays of Heavy right-handed Singlet neutrinos.

Fukujita + Yanagida

$$N \to \ell \phi \neq N \to \ell^c \phi^c$$

Fast sphaleron processes convert

$$\Delta B \simeq \frac{1}{3}(B-L)$$

$$\Delta B \simeq -\frac{1}{2}\Delta L$$

Problems: later

Heavy Leptons: Intermediaries in see-saw mechanism

$$\mathcal{L} = -N^T \lambda L H - \frac{1}{2} N^T M N$$

$$\rightarrow \quad m_\nu \simeq - m_D^T M^{-1} m_D$$

$$m_D = \lambda \langle H \rangle = \lambda v$$

- Small m_ν's $\rightarrow$ large M $\sim 10^{10-15}$ GeV
- N's appear in GUTs ($SO(10)$, $E(6)$) and 4-D string constructions
- Produced as a result of reheating after inflation, or preheating for heavy N's

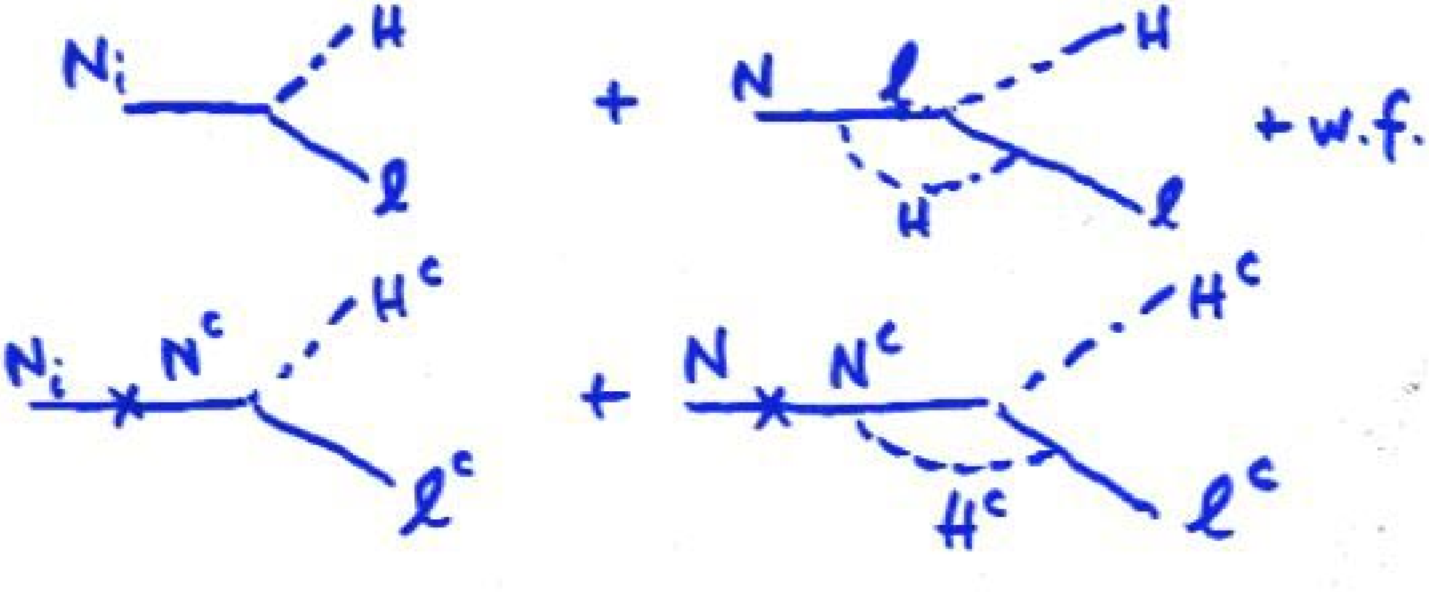
Giudice, Peloso, Riotto, Tkatchev hep-ph/9905242
Murayama et al (SUSY)

Sakharov Criteria

- $\Delta L \neq 0$ in decay
- CP violation
- Non-equilibrium during decay

First and Second

$$\epsilon_i = \frac{\Gamma(N_i \to \ell H) - \Gamma(N_i \to \ell^c H^c)}{\Gamma(N_i \to \ell H) + \Gamma(N_i \to \ell^c H^c)}$$



Results (for decay of lightest N_i)

- $$\epsilon_i = \frac{-3}{16\pi} \frac{1}{(\lambda^+\lambda)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[(\lambda^+\lambda)_{ij}{}^2\right] \frac{M_i}{M_j}$$

- $$Y_L = \frac{n_L}{s} \simeq \kappa \frac{\epsilon_i}{g^*} \simeq \kappa \cdot 10^{-2} \epsilon_i$$

  $\simeq 2 \frac{n_B}{s}$

  $\kappa \sim 10^{-1} - 10^{-2}$

- κ represents suppression because out of equ condition violated

M.A. Luty
Liu + Segrè
M. Plümacher
Covi, Roulet + Vissani
Campbell et al (SUSY)

Out of Equilibrium:

Must insure that

$$\Gamma(\ell H \to N) < H \quad \text{at } T \simeq M_i$$

Same as

$$\Gamma_{N_i} < H(M_i)$$

$$\rightarrow \boxed{\tilde{m}_i \equiv \frac{(\lambda^\dagger \lambda)_{ii} v^2}{M_i} < 2 \times 10^{-3} \text{ eV}}$$

- If $\tilde{m}_i > 2 \times 10^{-3}$ eV, κ gets smaller
- $\tilde{m}_i$ is not necessarily $= m_i$

So... <u>restrictions on λ</u>

Berger et al
Ellis et al
Kang et al
Joshipura + Paschos

- But λ defined in basis where M and $\ell^{\pm}$ mass matrices are diagonal. So only indirect info on yukawa textures.

Present simple model with direct information on neutrino masses as input.

Simple Model

Adopt:

(1) Maximal $\mu - \tau$ mixing

(2) Small angle MSW — $\theta = 0$

$\rightarrow$ e decouples

$$U^T m_\nu U = m_{diag} = \begin{pmatrix} m_2 & 0 \\ 0 & m_3 \end{pmatrix}$$

m_2 complex

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$m_\nu = \frac{1}{2} \begin{pmatrix} m_2 + m_3 & -m_2 + m_3 \\ -m_2 + m_3 & m_2 + m_3 \end{pmatrix}$$

$$= -v^2 \lambda^T M^{-1} \lambda$$

Work in basis where M is real, negative, diagonal

$$(m_\nu)_{ij} = v^2 \sum_k \lambda_{ki} \lambda_{kj} / M_k$$

Because of symmetric nature, 3 equ in 4 complex λ's

$$\lambda = \begin{pmatrix} a & d \\ c & b \end{pmatrix}$$

Look at two scenarios:

(I) $d = 0$ $\lambda = \begin{pmatrix} a & 0 \\ c & b \end{pmatrix}$

$\rightarrow \rightarrow$

$$a = \left(\frac{2M_2}{v^2} \, \frac{m_2 m_3}{m_2 + m_3} \right)^{1/2}$$

$$b = \left(\frac{M_3}{2v^2} \, (m_2 + m_3) \right)^{1/2}$$

$$c = b \left(\frac{m_3 - m_2}{m_3 + m_2} \right)$$

Easy description of near-degeneracy $c \ll b$

$$m_3 = m_2 (1 - \delta) \quad |\delta| \ll 1$$

To lowest order in δ

$$\tilde{m}_3 \equiv \frac{(\lambda^{+}\lambda)_{33}\, v^2}{M_3} \simeq m_3$$

Out of Equ

$\tilde{m}_3 < 2 \times 10^{-3}\, eV \rightarrow m_3 < 2 \times 10^{-3}$ eV

Not compatible

with $m_2 \simeq m_3$

and atmospheric data

even if we allow $\tilde{m}_3 \simeq 5 \times 10^{-2}$ eV

(II) $d = c$

$$\lambda = \begin{pmatrix} a & c \\ c & b \end{pmatrix}$$

(like λ_{up} in $SO(10)$)

Interesting solution for

$$c = a - \delta$$
$$b = a - \delta + \kappa$$

$|\delta|, |\kappa| \ll a$

$$a \simeq \left(\frac{m_3 M_3}{2v^2}\right)^{1/2}$$

$$\delta \simeq \left(\frac{2m_2 M_2}{v^2}\right)^{1/2}$$

$$\kappa \simeq \left(\frac{2m_2 M_3}{v^2}\right)^{1/2}$$

For consistency, require

- $|m_2| \ll m_3 \left(\frac{M_3}{4M_2} \right)$

Again, find

$$\tilde{m}_3 \simeq m_3$$

But now $m_3 \simeq 5 \times 10^{-2}\ \mathrm{eV}$
$> 2 \times 10^{-3}\ \mathrm{eV}$

- $Y_L \simeq 10^{-4}\ \epsilon_3$

(Extra suppression by factor of 10^{-2})

Faridoni et al hep-ph 9804261

→ A Nice Formula

$$\epsilon_3 = \frac{3}{8\pi}\left(\frac{|m_2| m_3 \, M_2 M_3}{v^4}\right)^{1/2} \cdot \left(\frac{M_3}{M_2}\right) \cdot \sin \tfrac{1}{2}\phi$$

Take $M_3 = 10^{12}$ GeV

$M_2 = 5 \times 10^{12}$ GeV

$m_2 = 2 \times 10^{-3}$ eV

$m_3 = 5 \times 10^{-2}$ eV

$\epsilon_3 = 2 \cdot 10^{-4} \sin \tfrac{1}{2}\phi$

$$\frac{n_B}{s} \simeq 0.5\, Y_L \simeq 5 \times 10^{-10}\, \phi_{CP}$$

OK for $\phi_{CP} \simeq 0.20$

Summary

(1) Out of Equ decay of heavy ν_R's (N's) provides very attractive scenario for $\Delta B \neq 0$

- ties in with see-saw
- parameters required are completely compatible with present neutrino spectrum

(2) A simple model presented in which $\frac{n_B}{s}$ written directly in terms of neutrino masses + mixing. Agreement with BBN for $m_3 \sim 5 \times 10^{-2}$ eV.

Problems:

- Need to produce N's.

  In SUSY $T_{RH} \lesssim 10^8$ GeV

  Need parametric resonance

- Need other reactions ($SU(2)_R$) to thermalize N's