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Workshop on Grand Unification and Proton Decay

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SO(10) Grand Unification and Leptogenesis

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SO(10) Grand Unification and Leptogenesis

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Grand Unification and Baryogenesis:

Baryogenesis requires:

1) B violation, 2) CP violation 3) Departure from equilibrium

GUTs could successfully explain baryogenesis.

Problem: SU(2) B+L global anomaly induced sphaleron transition are fast during $10^{12} GeV > T > 10^{2} GeV$

Solution: generate B-L asymmetry during this period:

Leptogenesis

The SO(10) GUT:

Fermion contents:

Fermions in the standard model:

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \equiv (3, 2, \frac{1}{6}); \qquad {u^c}_L \equiv (3, 1, -\frac{2}{3}); \qquad {d^c}_L \equiv (3, 1, \frac{1}{3});$$

$$\ell_L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \equiv (1, 2, -\frac{1}{2}); \qquad {e^c}_L = {e^+}_L \equiv (1, 1, 1)$$

Left-handed fermions in the SO(10) GUT belonging to the representation 16:

$$\Psi_L = \begin{pmatrix} u_1 & u_2 & u_3 & \nu_e \\ d_1 & d_2 & d_3 & e^- \end{pmatrix}_L + \begin{pmatrix} u_1^c & u_2^c & u_3^c & \nu_e^c \\ d_1^c & d_2^c & d_3^c & e^+ \end{pmatrix}_L .$$

$$16 = (4, 2, 1) + (\overline{4}, 1, 2)$$

The right-handed fermions can then be identified with the components of a $\overline{16}$ representation

$$\overline{\Psi}_R = \begin{pmatrix} u_1^c & u_2^c & u_3^c & \nu_e^c \\ d_1^c & d_2^c & d_3^c & e^+ \end{pmatrix}_R + \begin{pmatrix} u_1 & u_2 & u_3 & \nu_e \\ d_1 & d_2 & d_3 & e^- \end{pmatrix}_R .$$

$$\overline{16} = (\bar{4}, 2, 1) + (4, 1, 2)$$

Under the left-right symmetric group

$$G_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \equiv (3, 2, 1, \frac{1}{3}); \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R \equiv (3, 1, 2, \frac{1}{3});$$

$$\ell_L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \equiv (1, 2, 1, -1); \qquad \ell_R = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_R \equiv (1, 1, 2, -1)$$

where $Q = T_{3L} + T_{3R} + \frac{B-L}{2} = T_{3L} + Y$

The SO(10) symmetry breaking pattern is:

$$
\begin{array}{llr}
SO(10) \xrightarrow{M_U} & SU(4)_c \times SU(2)_L \times SU(2)_R & G_{PS} \\
\xrightarrow{M_1} & SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{(B-L)} & G_{LR} \\
\xrightarrow{M_R} & SU(3)_c \times SU(2)_L \times U(1)_Y & G_{std} \\
\xrightarrow{m_W} & SU(3)_c \times U(1)_Q & G_Q
\end{array}
$$

The gauge bosons belong to 45:

$$
\begin{aligned}
45 \quad = \quad & (8,1,1,0) + (1,3,1,0) + (1,1,3,0) + (1,1,1,0) \\
& + (3,2,2,-\frac{2}{3}) + (\bar{3},2,2,\frac{2}{3}) + (3,1,1,\frac{4}{3}) + (\bar{3},1,1,-\frac{4}{3})
\end{aligned}
$$

The Higgs fields are:

Scalar fields	SO(10) Repr	Transforms under G_{LR}	Transforms under G_{std}
η	210	(1,1,1,0)	(1,1,0)
Δ_R	126	(1,1,3,- 2)	(1,1,0)
Φ_{10}	10	(1,2,2,0)	(1,2,$\pm$ 1/2)
Φ_{126}	126	(1,2,2,0)	(1,2,$\pm$ 1/2)
Δ_L	126	(1,3,1,- 2)	(1,3, - 1)

Neutrino Masses and Leptogenesis:

The right-handed neutrino $N_{iR}, i = 1, 2, 3.$ interactions are:

$$\mathcal{L}_N = h_{i\alpha}\ \bar{N}_{Ri}\ \phi\ \ell_{L\alpha} + M_{ij}\ \overline{(N_{Ri})^c}\ N_{Rj}.$$

The mass terms become

$$\begin{aligned}\mathcal{L}_{mass} &= m_{D\alpha i}\ \nu_\alpha\ N_i^c + M_i\ N_i^c\ N_i^c \\ &= \begin{pmatrix} \nu_\alpha & N_i^c \end{pmatrix} \begin{pmatrix} 0 & m_{D\alpha i} \\ m_{Di\alpha} & M_i \end{pmatrix} \begin{pmatrix} \nu_\alpha \\ N_i^c \end{pmatrix}.\end{aligned}$$

The physical states are $\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu \\ N^c \end{pmatrix},$

where $\tan\theta = \frac{2M}{m_D}$. with mass eigenvalues

$$m_1 = -\frac{m_D^2}{M} \quad \text{and} \quad m_2 = M.$$

Majorana mass of $\mathbf{N}$ allows L-violating decays,

$$\begin{aligned} \mathbf{N_{Ri}} &\longrightarrow \ell_{\mathbf{jL}} + \bar{\phi}, \\ &\longrightarrow {\ell_{\mathbf{jL}}}^{\mathbf{c}} + \phi. \end{aligned}$$

The amount of lepton asymmetry in N_1 decay is given by,

$$\delta = -\frac{1}{8\pi}\frac{M_1}{M_2}\frac{\mathrm{Im}[\sum_\alpha (h^*_{\alpha 1} h_{\alpha 2}) \sum_\beta (h^*_{\beta 1} h_{\beta 2})]}{\sum_\alpha |h_{\alpha 1}|^2}$$

The out-of-equilibrium condition

$$\frac{|\mathbf{h}_{\alpha 1}|^2}{16\pi}\mathbf{M_1} < 1.7\sqrt{g_*}\frac{\mathbf{T^2}}{\mathbf{M_P}} \qquad \text{at} \quad \mathbf{T} = \mathbf{M_1},$$

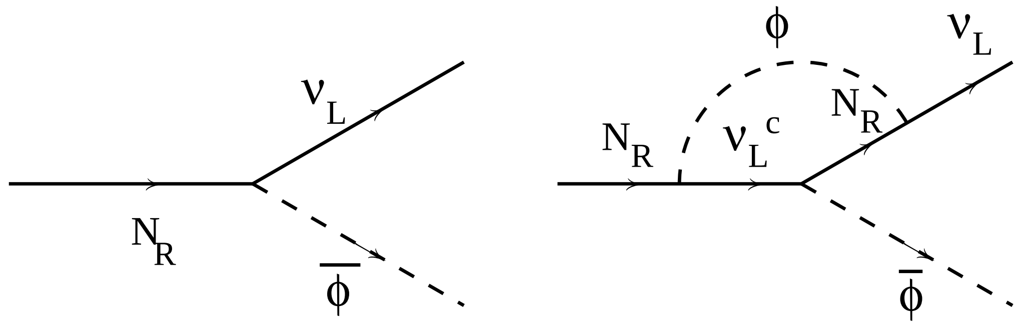
is satisfied for $M_1 > 10^8$ GeV and sphalerons convert this asymmetry into a baryon asymmetry $\frac{n_B}{s} = \frac{24+4n_H}{66+13n_H}\frac{n_{B-L}}{s}$

which is consistent with the BBN and WMAP

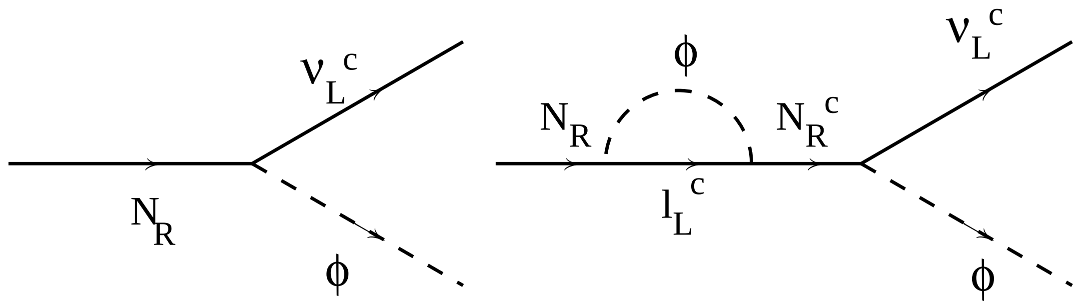
$$\frac{\mathbf{n_B}}{\mathbf{n_\gamma}} = (6.15 \pm 0.25) \times 10^{-10} \qquad \text{with} \quad \mathbf{s} = 7.04\mathbf{n_\gamma}$$

There are two sources of CP violation:

Vertex type diagrams interfering with tree level diagram. This is similar to the CP violation coming from the penguin diagram in K–decays (direct CP violation). [M. Fukugita and T. Yanagida, PLB 86]



Self energy diagram interfering with tree level diagram. This is similar to CP violation in $K - \bar{K}$ oscillation (indirect CP violation entering in the mass matrix). [M. Flanz, E.A. Paschos and US, PLB 95
L. Covi, E. Roulet and F. Vissani, W. Buchmuller and M. Plumacher]

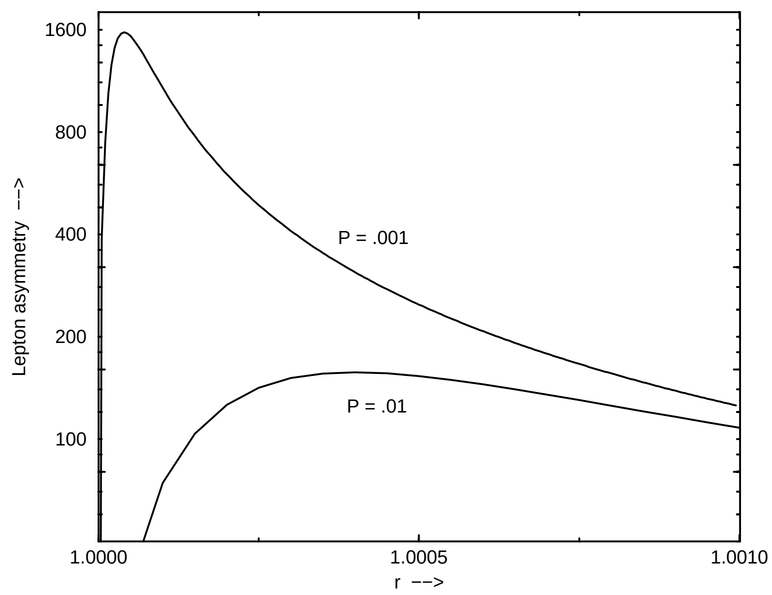


Resonant Leptogenesis

[M. Flanz, E.A. Paschos, J. Weiss and US, PLB 96

A. Pilaftsis, et al]

For CP violation of self-energy type, there is a resonant effect for small mass difference between N_{1R} and N_{2R}.



In left-right symmetric models there is another source of leptogenesis due to triplet scalar Δ_L [E. Ma and US, PRL 98 Lazarides and Q. Shafi, W. Grimus, T. Hambye, E. Ma and US]

The relevant interactions are

$$\mathcal{L} = \mathrm{f_{ij}}\ \mathbf{\Delta_L}\ \ell_{\mathrm{i}}\ \ell_{\mathrm{j}} + \mu\ \mathbf{\Delta_L^\dagger}\ \phi\ \phi + \mathrm{M}_{\mathbf{\Delta}} \mathbf{\Delta_L^\dagger} \mathbf{\Delta_L}$$

The vev of the triplet $\langle \Delta_L \rangle \sim \text{Const.} \frac{\langle \phi \rangle^2}{\langle \Delta_R \rangle}$ **gives neutrino masses:**

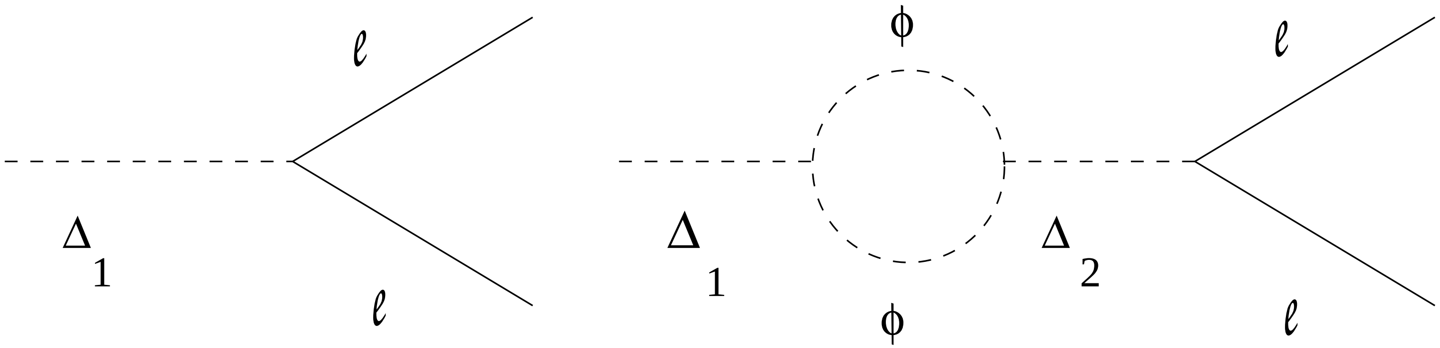
$$m_{\nu ij} = f_{ij} \langle \xi^0 \rangle$$

Lepton number violating decay modes of Δ_L are,

$$\mathbf{\Delta_L} \quad \rightarrow \quad \begin{cases} \ell\ \ell & (L = -2) \\ \phi^+\ \phi^+ & (L = 0) \end{cases}$$

CP violation comes from interference of tree level and one-loop self-energy type diagram

CP violation requires two triplet Higgs



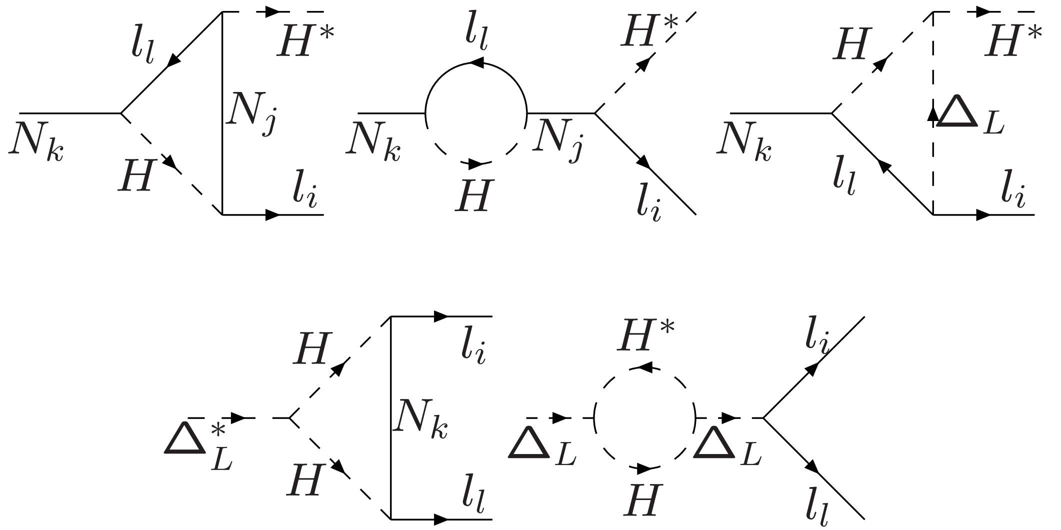
In this case CP violation comes from $\Gamma[\xi_a \longrightarrow \xi_b] \neq \Gamma[\xi_b \longrightarrow \xi_a]$

Similar to ν**—oscillations:** $\Gamma[\nu_a \longrightarrow \nu_b] \neq \Gamma[\nu_b \longrightarrow \nu_a]$

The tree level and the self energy type diagrams interfere to generate a lepton asymmetry of the universe, given by,

$$\delta \simeq \frac{\mathbf{Im}\left[\mu_1 \mu_2^* \sum_{\mathbf{k,l}} \mathbf{f_{1kl} f_{2kl}^*}\right]}{8\pi^2 (\mathbf{M_1^2} - \mathbf{M_2^2})} \left[\frac{\mathbf{M_1}}{\mathbf{\Gamma_1}}\right].$$

In SO(10) GUT, all these particles $N_R, \triangle_L$ and $\triangle_R$ take part in leptogenesis. [T. Hambye and G. Senjanovic, PLB 04
N. Sahu and US, PRD 06]



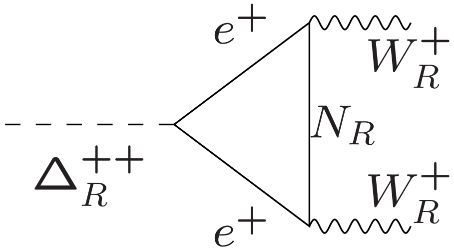
$\triangle_R$ interactions are suppressed due to small vev of $\triangle_L$.
The last diagram requires two $\triangle_L$

There are more processes contributing to leptogenesis.

Right-handed gauge bosons interactions allow lepton number violation

$$\Delta_R^{++} \quad \rightarrow \quad W_R^+ + W_R^+ \qquad \text{or} \qquad \ell^+ + \ell^+$$

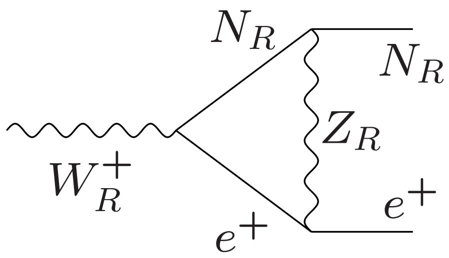
The corresponding new diagrams include

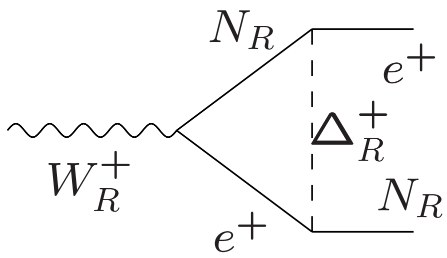


Right-handed gauge bosons decay can also violate lepton number

$$W_R^+ \rightarrow e^+ N_R \qquad \text{or} \qquad e^+ N_R^c$$

The corresponding new diagrams include





Out-Of-Equilibrium condition:

There are lepton number violating decays of

Δ_L, Δ_R, $W_R^{\pm}$, Z_R, N_3, N_2 and N_1

Assume, $M_{\Delta}, M_R \gg M_3 > M_2 > M_1$

At $\mathrm{T} = \mathrm{M}_1$, except for N_1 for other particles will disappear.

Fast interactions that can generate N_1 will also wash out any existing lepton asymmetry

Decays of N_1 will generate the final lepton asymmetry of the universe.

CP violation in leptogenesis are independent of CP violation at low energy [Branco, et al, Raidal and Ellis, US et al]

Assuming that the Dirac CP phase in the weak basis contribute to leptogenesis, strong limit on neutrino mass is possible: [Bari, Buchmuller, Plumacher]

$$\mathbf{m}_\nu < \mathbf{0.2}\,\mathrm{eV}$$

Including triplet Higgs and resonant conditions, this limit could be relaxed to 1 eV.

If N_1 interactions are not fast at any time, it may not affect lepton asymmetry generated by heavier particles like W_R or Δ_L.

Bounds on neutrino mass may not be present in that case.

Whether leptogenesis is possible in any SO(10) GUT will depend on the mass scales in the theory

Usually only large left-right symmetry breaking scales are allowed, which may marginally allow leptogenesis

D-parity violating theories may allow lower symmetry breaking scales

Higher dimensional gravitational interactions and threshold corrections can change some of the results for the symmetry breaking scales in the theory

SO(10) GUT with only doublet Higgs scalars:

Scalar fields	SO(10) Repr	Transforms under G_{LR}	Transforms under G_{std}
η	210	(1,1,1,0)	(1,1,0)
χ_R	16	(1,1,2,- 1)	(1,1,0)
Φ	10	(1,2,2,0)	(1,2,$\pm$ 1/2)
χ_L	16	(1,2,1,- 1)	(1,2, - 1/2)

One new singlet fermion S will be required for consistency.

Mixing of Φ with χ_L will break (B-L)

Type III see-saw neutrino masses is possible. Right-handed neutrinos ν_R and the singlet S can mix and have a small mass difference, generating resonant leptogenesis without fine tuning.

[S.M. Barr et al, PRL 04, PRD 05]

Both quarks and leptons could have see-saw masses leading to interesting phenomenology [K.S. Babu, J.C. Pati and F. Wilczek

B. Brahmachari, E. Ma and US, PRL 02]

D-parity violating models can accommodate interesting new scenarios of leptogenesis [Valle, et al PRL 06

Hirsch, Valle, Malinsky, Romao and US PRD 07(RC)]

SUMMARY:

There are several sources of leptogenesis in SO(10) GUTs.

In SO(10) GUTs with triplet Higgs scalars, there are interesting predictions, but some of these predictions requires further investigation.

In SO(10) GUTs with only doublet Higgs scalars, leptogenesis can have some interesting realizations with phenomenological consequences.