Leptogenesis

Origin of the Matter-Antimatter Asymmetry in the Universe

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Neutrino Mass

Atmospheric and solar neutrino oscillation experiments show the non-vanishing neutrino masses

$$\Delta m^2_{\mathrm{atm}} \simeq 3 \times 10^{-2}\mathrm{eV}$$

$$\Delta m^2_{\mathrm{sol}} \simeq 7 \times 10^{-5}\mathrm{eV}$$

Why is neutrino mass so small?

Theory of Neutrino Mass

- **Yukawa coupling** $\mathcal{O} = h\bar{\nu}_R \ell H \quad ; \; \ell^t = (\nu, e)$

We need extremely small coupling to explain the small neutrino mass.

$$m_\nu = h < H > \quad \text{with} \;\; h \simeq 10^{-13}; \quad \text{c.f.} \;\; h_t \simeq \mathcal{O}(1)$$

Neutrinos are Dirac particles.

- **Dimension =5 operator** $\mathcal{O} = \frac{1}{M} \ell \ell H H$

Weinberg (1979)

The small neutrino mass is explained by a large mass M beyond the standard model scale.

$$m_\nu = \frac{1}{M} < H >^2$$

Neutrinos are Majorana particles.

Good Reasons for the Majorana Neutrino

- The Grand Unification

The GUT breaking at scale M generates the D=5 operator for neutrino mass. It predicts the neutrino mass

$$m_\nu \simeq 0.01 - 0.1\mathrm{eV} \quad \text{for} \quad M \simeq 10^{15-16}\mathrm{GeV}$$

- The matter-antimatter asymmetry in the universe

Baryogenesis requires B-L breaking interactions at high energies which may induce the D=5 operator for neutrino mass.

B and L Non-conservation in The Standard Model

- B-number conservation is broken by SU(2) instanton effects. ‘t Hooft (1976)

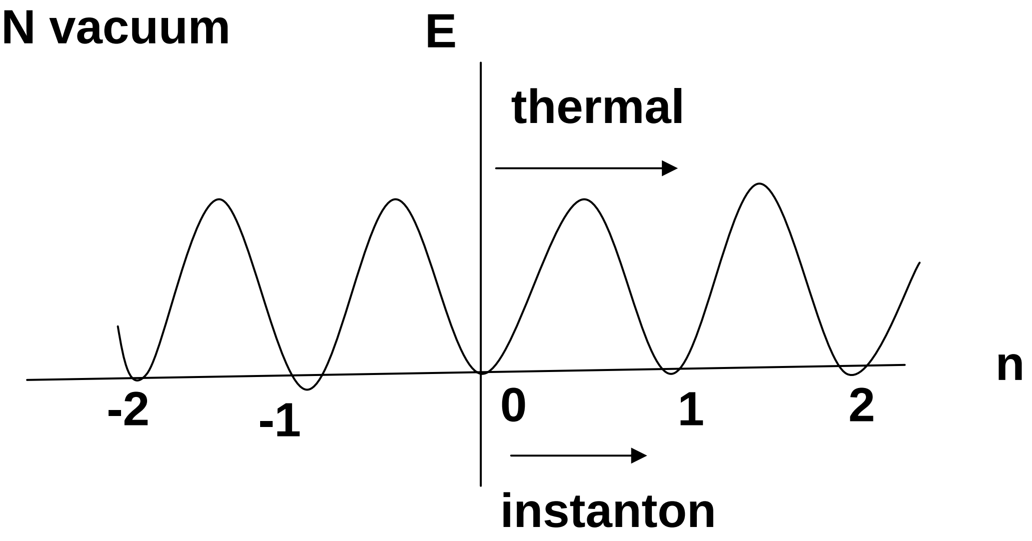
- But, it is strongly suppressed and hence the proton is stable.

$$\Gamma \simeq \exp(-16\pi^2/g^2) \sim 10^{-170}$$

- L-number is also broken by the instanton effects. However, it is very important that the B-L is conserved.

- The B and L violating processes are no longer suppressed at high temperatures.

Kuzmin, Rubakov , Shaposhnikov (1885)



- At T>O(100) GeV, B and L violating transitions are in thermal equilibrium.

- All B asymmetry is washed out if there is no B-L asymmetry in the early universe.

$$\Delta B = C \times \Delta(B - L)_0$$

- We need some B-L violating interactions at high energies to explain the matter-antimatter asymmetry in the present universe.

- If the electroweak phase transition is the first order, the baryon asymmetry may be created at the EW phase transition. This predicts the Higgs mass,

$$m_H < 80\mathrm{GeV}.$$

- However, the present bound on the Higgs mass from LEP is

$$m_H > 114\mathrm{GeV}.$$

- The electroweak baryogenesis is excluded in the standard model.

B-L violation to create the B asymmetry in the universe

- B-L violating interactions at high energies generate B-L violating operators at low energies.

- The lowest dimensional operator for the B-L violation is the D=5 operator inducing the small Majorana mass for neutrino.

$$\mathcal{O} = \frac{1}{M}\ell\ell H H$$

- Thus, the presence of B asymmetry in the Universe predicts neutrino-less Double Beta Decay !!!

  (instead of proton decay)

- But, lepton-Higgs scattering amplitude exceeds the Born unitarity bound at E> M.

- Thus, the D=5 operator must be generated by a new physics at ~ M.

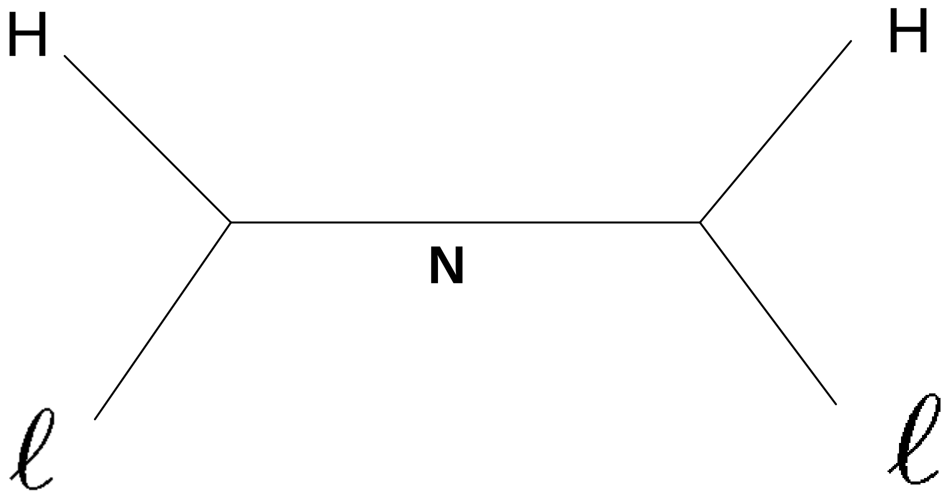
- There are two possibilities:

(a) Boson exchange

(b) Fermion exchange.

- We consider Fermion N exchange, since it is a prediction of a class of GUT, T,GRS (1979)

  and it’s decay can naturally produce the B-L asymmetry in the early universe.



$$\simeq \frac{1}{M}\ell\ell HH$$

The seesaw model

- The standard model + heavy right-handed neutrinos N :

$$\mathcal{L} = hN\ell H \ + \ \frac{1}{2}MNN \ + \ h.c.$$

$$m_D = h < H >$$

- The integration of N generates small neutrino masses.

$$\mathcal{O} = \frac{h^2}{M}\ell\ell HH \ \rightarrow \ m_\nu \simeq \frac{m_D^2}{M}$$

Leptogenesis

Fukugita, TY (1986)

- The heavy N has two decay modes;

$$N \to \ell + H \quad ; \quad N \to \bar{\ell} + \overline{H}$$

- If CP is broken in the decay process, the two decay modes have different rates. Thus, the N decay produces lepton asymmetry.

- The lepton asymmetry is converted into the baryon asymmetry by the KRS effects.

$$\Delta L \to \Delta B$$

CP violation

- The Yukawa coupling is given by 3 by 3 matrix.

$$\mathcal{L} = h_{ij} N_i \ell_j H + \frac{1}{2} M_i N_i N_i + \text{h.c.}$$

- The Yukawa matrix has 9 complex parameters which contain 9 phases.

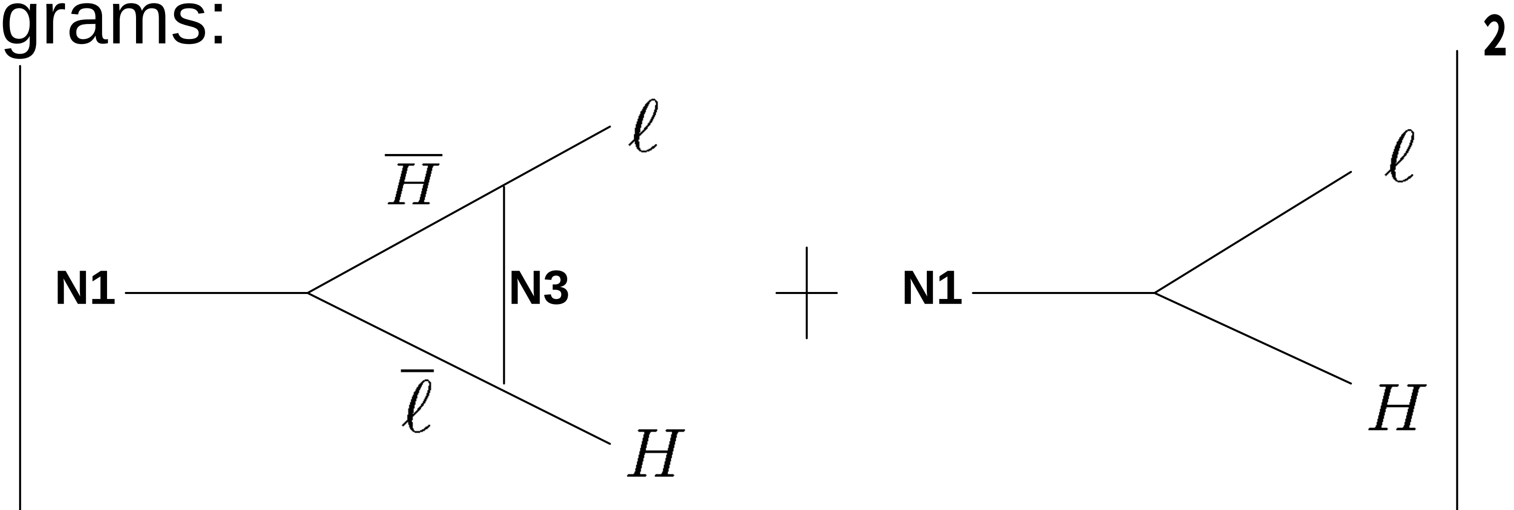
  But, 3 of them can be absorbed into the phases of wave functions ℓ. Thus, we have 6 CP-violating phases.

- We assume a mass hierarchy,

$$M_1 < M_2 < M_3.$$

- We consider the decay of the lightest heavy Majorana N_1, since the L asymmetries produced via heavier $N_{2,3}$ decays are washed out by the L-violating processes induced by the lightest N_1.

- The lepton asymmetry arises from interference diagrams:



The lepton asymmetry parameter ϵ

$$\epsilon = \frac{\Gamma(N_1 \to H + \ell) - \Gamma(N_1 \to \overline{H} + \bar{\ell})}{\Gamma(N_1 \to H + \ell) + \Gamma(N_1 \to \overline{H} + \bar{\ell})}$$

$$\simeq \frac{3}{16\pi}\frac{1}{(hh^\dagger)_{11}}\mathrm{Im}[(hh^\dagger)_{1j}]^2(\frac{M_1}{M_j})$$

$$\simeq \frac{3}{16\pi} m_{\nu_3} \frac{M_1}{< H >^2}\delta \qquad \leftarrow m_{\nu_3} \simeq \frac{h_{33}^2}{M_3} < H >^2$$

For the CP violating phase $\delta \simeq \mathcal{O}(1)$

$$\epsilon \simeq 10^{-6}(\frac{M_1}{10^{10}\mathrm{GeV}})(\frac{m_{\nu_3}}{0.05\mathrm{eV}})$$

- The L asymmetry is converted into the B asymmetry by KRS effects: $\epsilon \rightarrow \epsilon_B$

$$\epsilon_B = (28/79)\epsilon$$

- The final baryon asymmetry is given by

$$\eta_B = \frac{n_B}{n_\gamma} = D\kappa\epsilon_B$$

- D is the dilution factor due to reheating of photons and

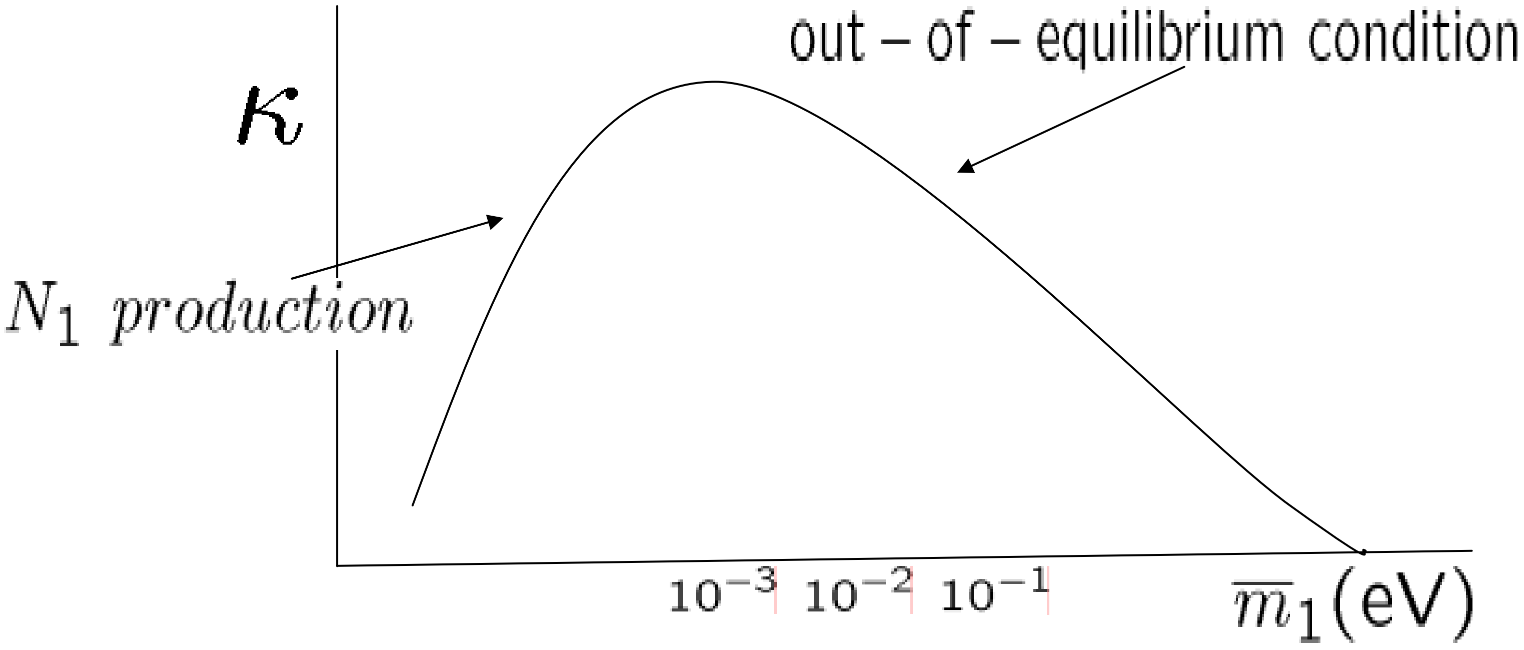
$$D = n_\gamma / n_\gamma^{\text{rec}} \simeq 1/30 \quad .$$

- κ is the dynamical factor due to wash-out processes.

- κ is estimated by solving the Boltzmann equations.

$$\kappa \simeq 2 \times 10^{-2}\left(\frac{0.01\text{eV}}{\overline{m}_1}\right)^{1.1}$$

Buchmuller, Bari, Plumacher



The out-of-equilibrium condition for N_1 decay

Sahkarov (1967)

- The decay rate < $H(\mathrm{exp})$ at $T \simeq M_1$

$$\Gamma_{N_1} \simeq \frac{1}{8\pi}(h^\dagger h)_{11} M_1 \quad ; \quad H(\mathrm{exp}) \simeq \sqrt{g}\frac{M_1^2}{M_{\mathrm{PL}}}$$

$$\longrightarrow \qquad \overline{m}_1 = \frac{m_D^\dagger m_D}{M_1} < 10^{-3}\mathrm{eV}$$

c.f. $\sqrt{m_{\mathrm{sol}}^2} \simeq 0.8\times 10^{-2}\mathrm{eV}$; $\sqrt{m_{\mathrm{atm}}^2} \simeq 0.5\times 10^{-1}\mathrm{eV}$

We expect $\overline{m}_1 \simeq 10^{-2} - 10^{-1}\mathrm{eV}.$

- The final baryon asymmetry is given by

$$\eta_B \simeq 10^{-2}\kappa\epsilon$$

$$\simeq \kappa 10^{-8}(\frac{M_1}{10^{10}\mathrm{GeV}})(\frac{m_{\nu_3}}{0.05\mathrm{eV}})$$

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

- The observation, $\eta_B(\mathrm{obs}) \simeq 6 \times 10^{-10}$, suggests

$$M_1 \simeq 10^{10}\mathrm{GeV}.$$

- The mass for the heaviest Majorana neutrino, N_3 :

$$m_{\nu_3} \simeq \frac{m_{D3}^2}{M_3} \simeq 0.05\mathrm{eV}$$

$$\longrightarrow \quad M_3 \simeq 10^{15}\mathrm{GeV} \quad \text{for} \quad m_{D3} \simeq m_t.$$

- If one assumes a mass hierarchy

$$M_3 : M_2 : M_1 \simeq m_t : m_c : m_u$$

one obtains

$$M_1 \simeq 10^{10}\mathrm{GeV}.$$

- The baryon asymmetry in the present universe is naturally explained by SO(10) GUT-like seesaw model.

$$M_1 \simeq 10^{10}\mathrm{GeV}$$

The low-energy predictions

1. CP violation in neutrino oscillation

2. Neutrino-less double beta decay

CP violation

- The seesaw model has 6 CP-violating phases.
- One combination of them contributes to Leptogenesis.
- The CP-violating phase measured by neutrino-oscillation experiments is a independent combination of 6 phases.
- We are unable to predict the phase in neutrino oscillation unless we restrict the seesaw model.

Frampton,Glashow,TY (2002)

Neutrino-less double beta decay

- There are three mass spectra suggested from neutrino oscillation experiments.

(a) normal hierarchy : $m_3 > m_2 > m_1$

(b) inversed hierarchy : $m_2 \simeq m_1 > m_3$

(c) degenerate masses : $m_3 \simeq m_2 \simeq m_1$

- All are consistent with Leptogenesis.

The prediction on $m_{\nu_e\nu_e}$, which induces the double beta decay

- For the case (c),

$$m_{\nu_e\nu_e} \simeq \mathcal{O}(0.1)\mathrm{eV}$$

- For the cases (a) and (b), it is difficult to predict the mass element $m_{\nu_e\nu_e}$.

- However, if the hierarchy is sufficiently large, one may predict the $m_{\nu_e\nu_e}$. Branco et al (2002)

- For the case (a); $m_3 > m_2 >> m_1$,

$$m_{\nu_e\nu_e} \simeq (1-4) \times 10^{-3}\mathrm{eV}$$

- For the case (b); $m_2 \simeq m_1 >> m_3$,

$$m_{\nu_e\nu_e} \simeq (1-7) \times 10^{-2}\mathrm{eV}$$

The Summary

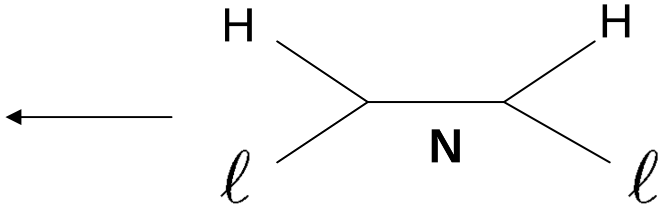
- The heavy Majorana Neutrino N explains the two important parameters;

(A) small neutrino mass

(B) baryon asymmetry in the
present universe

(A) The exchange of the N induces D=5 operator

$$\mathcal{O} = \frac{1}{M}\ell\ell HH$$



The neutrino mass:

$$m_\nu \simeq \frac{1}{M} < H >^2$$

$M \simeq 10^{15}$GeV for $m_\nu \simeq 0.05$eV

The neutrino is Majorana particle.

(B) The decay of N_1 in the early universe produces lepton asymmetry, which is converted to the baryon asymmetry in the present universe.

$$N_1 \to \ell + H \quad \text{or} \quad \bar{\ell} + \overline{H}$$

$$\frac{n_B}{n_\gamma} \simeq 10^{-9} \left(\frac{m_{\nu_3}}{0.05\text{eV}}\right)\left(\frac{M_1}{10^{10}\text{GeV}}\right)$$

The observation 6×10^{-10} suggests

$$M_1 \simeq 10^{10}\text{GeV}.$$

- Interesting mass hierarchy:

$$M_1 : M_3 \simeq m_u : m_t \simeq 10^{-5} : 1$$

↓

SO(10)-like unification

Model independent prediction

The neutrino-less double beta decay is a prediction of the Baryogenesis.

- The B and L are not conserved in the early universe of T> a few 100 GeV. Only (B-L) is conserved.
- Thus, the present B number is given by the primordial (B-L) asymmetry.

$$\Delta B|_{\text{present}} = C(B-L)|_0$$

- To explain the B asymmetry in the present universe, we need (B-L) violating interactions at high energies.

(B-L) violating operators at low energies

- Such B-L violating interactions may induce B-L violating operators at low energies.

- The lowest dimensional operator is

$$\mathcal{O} = \frac{1}{M}\ell\ell HH \quad \longleftarrow \quad \Delta(B-L) = -2$$

which generates small Majorana mass for light neutrino.

- The proton decay is irrelevant to the Baryogenesis, since operators contributing to the proton decay conserve (B-L).

$$QQQ\ell \ \leftarrow \Delta(B-L)=0$$

- **The neutrino-less Double Beta Decay is the most important experiment for testing the idea of Baryogenesis by Sahkarov (1967).**

$$A \to A' + e + e \qquad \leftarrow \quad \Delta(B-L) = -2$$