“FLAVOURED LEPTOGENESIS AND TYPE-II SEESAW MECHANISM WITH TWO HIGGS TRIPLET SCALARS”

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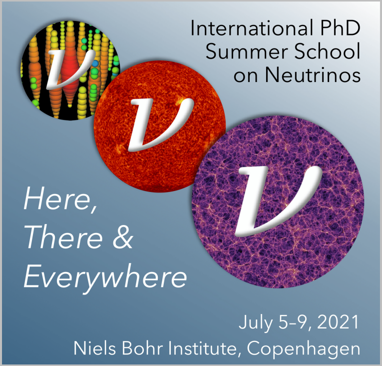

Introduction:

- Neutrino mass generation

Figure: The Super-K Experiment [$\mu^- \longrightarrow e^- + \overline{\nu}_e + \nu_\mu$]

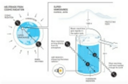

Figure: The Sudbury Neutrino Detector [$p + p \longrightarrow d + e^+ + \nu_e$]

Solar and atmospheric neutrino deficit

- In the Super-Kamiokande experiment in Japan, many fewer muon neutrinos (ν_μ) were found to arrive than the number predicted by the theory.
- The number of detected electron neutrinos (ν_e) on earth was only $\frac{1}{3}$ of the number predicted by the Standard Model.

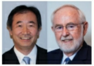

Figure: **Nobel Prize for Physics 2015**- *Takaaki Kajita and Arthur B. McDonald "For the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Introduction:

- Neutrino mass generation
- Seesaw mechanism

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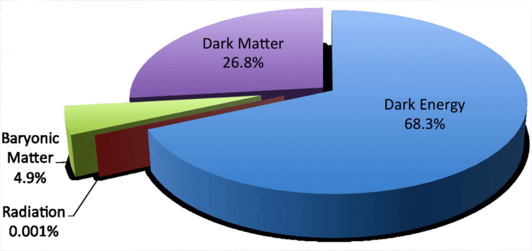
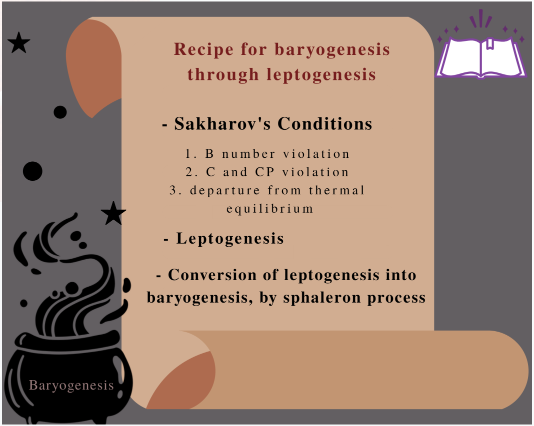
- Seesaw mechanism
- Baryogenesis

$$\eta_B = \frac{(n_B - n_{\overline{B}})}{n_\gamma},$$



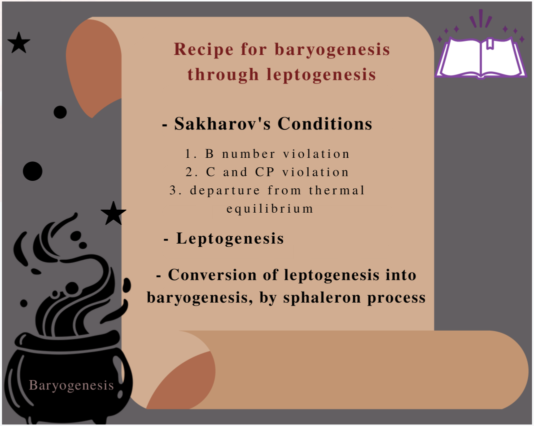
Introduction:

- Neutrino mass generation
- Seesaw mechanism
- Baryogenesis
- Sakharov's conditions



Introduction:

- Neutrino mass generation
- Seesaw mechanism
- Baryogenesis
- Sakharov's conditions
- Leptogenesis



Introduction:

- Neutrino mass generation
- Seesaw mechanism
- Baryogenesis
- Sakharov's conditions
- Leptogenesis
- Flavoured triplet leptogenesis

Motivation:

- Neutrino mass generation through type-II seesaw mechanism
- Baryon asymmetry estimation through flavoured triplet leptogenesis

Model description

- Two triplet Higgs scalars with hypercharge, $\mathcal{Y} = 2$

$$T_1 = \begin{pmatrix} \frac{\delta_1^+}{\sqrt{2}} & \delta_1^{++} \\ \delta_1^0 & -\frac{\delta_1^+}{\sqrt{2}} \end{pmatrix}, \quad T_2 = \begin{pmatrix} \frac{\delta_2^+}{\sqrt{2}} & \delta_2^{++} \\ \delta_2^0 & -\frac{\delta_2^+}{\sqrt{2}} \end{pmatrix}$$

- Triplet vacuum expectation values:

$$< \delta_1^0 >= \omega_1 = |\omega_1| e^{i\alpha}, \quad < \delta_2^0 >= \omega_2$$

- $\omega_1, \omega_2 \ll v$,
- $M_{T_1} \gg M_{T_2}$, $\quad M_{T_2} \sim 10^9$ GeV

[Avinanda Chaudhuri, Biswarup Mukhopadhyaya (2016)]

Model description

- Extended Lagrangian

$$\mathcal{L} = Tr[(D_\mu T_k)^\dagger (D^\mu T_k)] - \frac{Y_{ij} L_i^T C_i \sigma T_k L j}{\sqrt{2}},$$

- $V(\phi, T_1, T_2) =$
$-m_\phi^2 \phi^\dagger \phi + \frac{\lambda}{2}(\phi^\dagger \phi)^2 + M_T^2 Tr(T_k^\dagger T_l) + \frac{(\lambda_k + \lambda_l)}{2}[Tr(T_k^\dagger T_l)]^2 - \frac{\lambda_2}{2} Tr[(T_k^\dagger T_l)^2] + \lambda_4 \phi^\dagger \phi Tr(T_k^\dagger T_l) + g Tr(T_1^\dagger T_2) Tr(T_2^\dagger T_1) + g' Tr(T_1^\dagger T_1) Tr(T_2^\dagger T_2) + \lambda_5 \phi^\dagger [T_k, T_l^\dagger] \phi + (\mu_k \phi^\dagger T_k i \sigma_2 \phi^* + h.c.)$

- Lepton number breaking trilinear term $\mu_k \phi^\dagger T_k i \sigma_2 \phi^*$ in the potential $V(\phi, T_1, T_2)$, $\mu_1 = |\mu_1| e^{i\beta}$

[Avinanda Chaudhuri, Biswarup Mukhopadhyaya (2016)]

Type-II seesaw mechanism

Neutrino mass generation

$$M_\nu = M_\nu^{(1)} + M_\nu^{(2)}$$

$$= Y_1 \omega_1 cos\alpha + Y_2 \omega_2$$

- $M_\nu^{(i)} = \omega_{T_{(i)}} Y_{T_{(i)}}$
- $\omega_{T_{(i)}} = \frac{\mu v^2}{2M_{T_{(i)}}}$
- light neutrino mass $M_\nu \propto \frac{1}{M_T}$,

Neutrino mass matrix

- Two-zero texture B_2: [Madan Singh (2020)]

$$B_2 = \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

- Z_3 horizontal symmetry
- disfavours Inverse Hierarchy (IH) of neutrino mass

Neutrino mass matrix

- Zero texture: $(m_\nu)_{ab} = (m_\nu)_{\alpha\beta} = 0$, $ab \neq \alpha\beta$
- Mass matrix elements:

$$(m_\nu)_{pq} = \sum_{i=1}^{3} (U_{pi} U_{qi} \lambda_i), \tag{1}$$

- $U \rightarrow$ PMNS Matrix
- $\lambda_1 = m_1 e^{2i\rho}$, $\lambda_2 = m_2 e^{2i\sigma}$, $\lambda_3 = m_3$
- ρ and $\sigma \rightarrow$ Majorana phases
- m_1, m_2, $m_3 \rightarrow$ neutrino mass eigen values

Neutrino mass matrix elements: Parameter space study

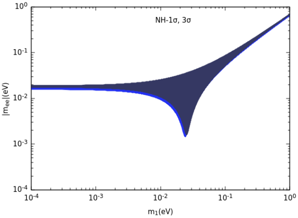


Figure: $m1$ vs $|m_{ee}|$ in eV

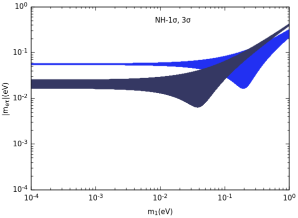


Figure: $m1$ vs $|m_{e\tau}|$ in eV

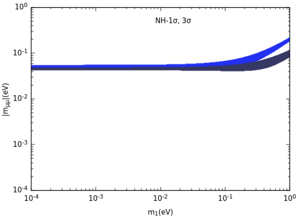


Figure: $m1$ vs $|m_{\mu\mu}|$ in eV

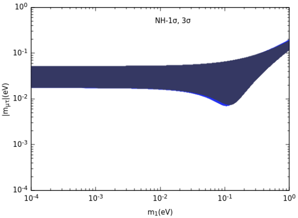


Figure: $m1$ vs $|m_{\mu\tau}|$ in eV

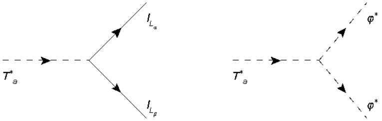
Neutrino mass matrix

- $$M_\nu = \begin{bmatrix} Ae^{i\phi_A} & 0 & Be^{i\phi_B} \\ 0 & Ce^{i\phi_C} & De^{i\phi_D} \\ Be^{i\phi_B} & De^{i\phi_D} & 0 \end{bmatrix}$$
- $\Sigma = m_1 + m_2 + m_3 \approx 0.1459eV < 0.16eV$
- The chosen neutrino mass matrix:

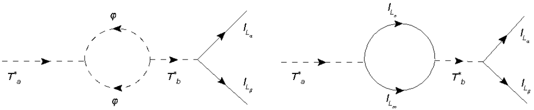
$$M_\nu = \begin{bmatrix} 0.04135 & 0 & 0.03411 \\ 0 & 0.05465 & 0.05085 \\ 0.03411 & 0.05085 & 0 \end{bmatrix}.$$

Triplet decay modes

- Tree level decay diagram:



- One-loop decay diagram:



[R. Gonzalez Felipe, F.R. Joaquim, and H. Serodio (2013)]

CP asymmetry parameter

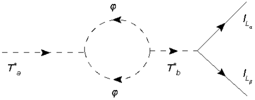
- Total CP asymmetry:

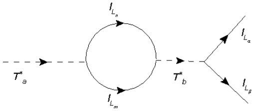
$$\epsilon = \epsilon_{\not{L},\not{F}} + \epsilon_{\not{F}}$$

- Purely flavoured case:

$$\epsilon = \epsilon_{\not{F}},$$

- Condition: $B_l \gg B_\phi$





Purely Flavoured Leptogenesis

- Fully flavoured CP asymmetry parameter: [Branco et al (2012)]

$$\epsilon_{\alpha\beta} = \frac{M_{T_2}(B_l B_\phi)^{\frac{1}{2}}}{4\pi v^2} \frac{c Im[(M_\nu^{(2)})_{\alpha\beta}(M_\nu^{(1)*})_{\alpha\beta}]}{[Tr(M_\nu^{(2)\dagger} M_\nu^{(2)})]^{\frac{1}{2}}}$$

$$\sum_{\alpha,\beta} \epsilon_{\alpha\beta} = 0$$

Fully flavoured CP asymmetry parameters

$$\epsilon_{ee} \propto \frac{A^2 \times f(\omega_1, \omega_2, v, M_T, \alpha, \phi)}{\sqrt{A^2 + 2(B^2 + D^2) + C^2}},$$

$$\epsilon_{e\tau} \propto \frac{B^2 \times f(\omega_1, \omega_2, v, M_T, \alpha, \phi)}{\sqrt{A^2 + 2(B^2 + D^2) + C^2}},$$

$$\epsilon_{\mu\mu} \propto \frac{C^2 \times f(\omega_1, \omega_2, v, M_T, \alpha, \phi)}{\sqrt{A^2 + 2(B^2 + D^2) + C^2}},$$

$$\epsilon_{\mu\tau} \propto \frac{D^2 \times f(\omega_1, \omega_2, v, M_T, \alpha, \phi)}{\sqrt{A^2 + 2(B^2 + D^2) + C^2}},$$

Lepton asymmetry plots: for different branching ratios

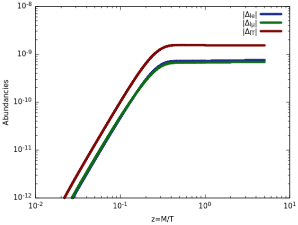
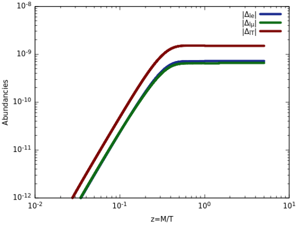


Figure: $B_l = 0.99999$



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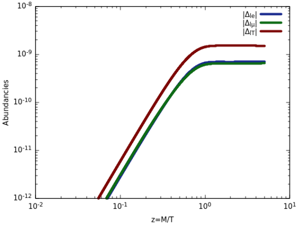

Figure: $B_l = 0.99$

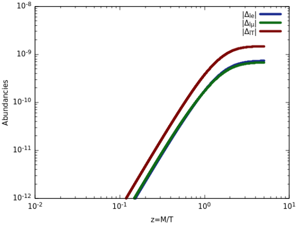

Figure: $B_l = 0.50$

Result

- Baryon asymmetry:

$$\eta_B = 3c_{sph} \sum_{\alpha,\beta} A^{-1}_{\alpha\beta} \Delta_{l_\beta}$$

$$c_{sph} = \frac{28}{79}, \quad A = \begin{pmatrix} -\frac{151}{179} & \frac{20}{179} & \frac{20}{179} \\ \frac{25}{358} & -\frac{344}{537} & \frac{14}{537} \\ \frac{25}{358} & \frac{14}{537} & -\frac{344}{537} \end{pmatrix}$$

[Davidson, Nardi, Nir (2008)]

Result

- Baryon asymmetry:

$$\eta_B = 3c_{sph} \sum_{\alpha,\beta} A^{-1}_{\alpha\beta} \Delta_{l_\beta}$$

- Result table:

B_l	η_B
0.99999	-5.24×10^{-10}
0.9999	-5.30×10^{-10}
0.99	5.85×10^{-10}
0.50	5.34×10^{-10}

Why phase α ?

$$T_1^{++} \longrightarrow T_2^{++} + h,$$
$$T_2^{++} \longrightarrow l_i^+ l_j^+,$$

The mixing between two triplet scalars brings the scope where the mass difference between T_1^{++} and T_2^{++} is sufficient to kinematically allow the transition $T_1^{++} \longrightarrow l_i^+ l_j^+ h$. It gives rise to a spectacular signal $T_1^{++} \longrightarrow l_i^+ l_j^+ h$ in the context of LHC.

[Avinanda Chaudhuri, Biswarup Mukhopadhyaya (2016)]

Conclusion

- Type-II seesaw mechanism and baryon asymmetry
- Future work

Thank you!

Summer School on Neutrinos

Here, There & Everywhere

July 5–9, 2021

Niels Bohr Institute, Copenhagen

Back-up slides

Bound on triplet vev

- Upper bound from ρ-parameter:

$$\rho = \frac{v^2 + 2\omega_1^2 + 2\omega_2^2}{v^2 + 4\omega_1^2 + 4\omega_2^2},$$

- Lower bound from LVF processes

Initial values taken for numerical analysis

- $$\Sigma_T(z \ll 1) = \Sigma_T^{eq}(z \ll 1)$$
- $$\Delta_T(z \ll 1) = 0, \quad \Delta_{l_\alpha}(z \ll 1) = 0,$$