"Failure is an incredible learning experience.
It teaches you humility.
It teaches you to work harder.
It is the first step to understanding."

Richard Feynman

1
Introduction

In the beta decay reaction ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-}$, the emitted electron must have a stable energy. But, in 1914, after many experiments performed by Lise Meitner and Otto Hahn, James Chadwick, using a magnetic spectrometer and an electron counter; they anticipated that the energy spectrum of electron was rather continuous. This evidence of unstability in the electron energy was further confirmed and proved by Charles Drummond Ellis and William Alfred Wooster in 1927 through an experiment on radium E (bismuth-210). This unsettling problem was first addressed by Wolfgang Pauli in December 1930 in a letter he sent to his colleagues. In his letter, he mentioned that there might be a possibility of existence of a particle which has properties: light, neutral, weakly interacting attributed to it. This new particle accompanies the electron and thus, carries off a part of the electron energy. In an eventful year 1932, neutron was discovered by James Chadwick, but unfortunately due to its massiveness, it ruled out the criteria to be the particle proposed by Pauli. Thus, to differentiate the neutrons from Pauli's particle, Enrico Fermi coined it as "*neutrinos*" at the Solvay conference in 1933. The beta decay was again rebuilt by Fermi, where a neutron decays to proton, electron and a neutrino. This model was built on the basis of neutrino hypothesis which suggested it to be spin $\frac{1}{2}$ particle with possibility of zero mass or mass much less than that of electron.

A popular method to detect neutrinos was put forward by Bruno Pontecorvo in 1946 by the use of inverse beta decay process, analogous to the chlorine-argon reaction which leads to the observation of argon decay. Based on this idea, Frederick Reines and Clyde Cowan started setting various experiments for the detection of neutrinos[1]. They finally succeeded in their project named "Poltergiest" which however required some alterations in order to produce sufficiently significant neutrino signals. This time they adequately decreased the background, thereby letting the neutrino signal a significance above 4σ. However, this was not the end as there were two more flavors of neutrino yet to be detected. The neutrino that was detected was the electron neutrino as in beta decay it is emitted along with an electron. In late 40's, the decay of charged pion into a muon and neutrino was observed. The neutrino emitted in this decay was considered as muon-neutrino which differed from electron-neutrino. In 1962, muon-neutrinos were detected in the spark chamber and this discovery won the Nobel prize in 1988. Again 25 long years after the discovery of tau lepton by Martin Perl and his team at SLAC electron-positron ring, tau-neutrino was discovered. This discovery was made at the Fermilab in an emulsion experiment named DONUT.

Neutrino oscillation is a well established quantum mechanical phenomena which states that a neutrino produced with a certain lepton family number (i.e. electron, muon and tau) is later observed to change its lepton family number. This idea of neutrino oscillation was suggested by Bruno Pontecorvo even when only one flavor of neutrino was detected. Later on, after the discovery of muon-neutrino, Pontecorvo generalized the idea of neutrino oscillation for two neutrinos[2, 3]. V. Gribov and B. Pontecorvo proposed the very first theory of two-neutrino mixing in 1969[4]. It is said that, the two-neutrino mixing phenomenology had been proposed long back in 1962 by Z. Maki, M. Nakagawa and S. Sakata. On the basis of their assumption for two neutrino lepton mixing matrix according to which ν_1 and ν_2 are represented through linear combination of ν_e and ν_μ. This concept was further generalized for three neutrinos by Pontecorvo, Maka, Nakagawa and Sakata[5]. Thus, we will now discuss the various theoretical and experimental developments in this sector in the following section.

1.1 Present scenario of neutrinos

1.1.1 Theoretical developments:

Neutrino oscillation is a phenomena which opens up a window for explaining the massiveness of neutrinos along with its additional properties which remained unaddressed in the Standard Model of particle physics. Thus, it gained much popularity in the theoretical as well as experimental sector of particle physics. Neutrino oscillation was first suggested by Pontecorvo in the 1960's. Whereas, its experimental discovery was made by Super-Kamiokande Observatory and Sudbury Neutrino Observatories which was recognised by the 2015 Noble Prize shared by Takaaki Kajita and Arthur B. McDonald. Neutrino physics has come up with some benchmark evidences for developing new physics for elementary particles thereby probing into the evolution of the Universe. It has also provided physics beyond the SM by incorporating neutrino mass and mixing. A unitary matrix named after Pontecorvo, Maka Nakagawa and Sakata, which is known as the PMNS matrix or leptonic mixing matrix[5] builds a relation between the mass eigenstates and flavor eigenstates of the neutrinos. This matrix is parametrized with the help of three mixing angles θ_{12}(solar), θ_{13}(reactor), θ_{23}(atmospheric) and a physical CP-violating phase(δ_{CP})[5]. Though initially the reactor mixing angle was considered to be zero, but later on with the advancement of many neutrino oscillation experiments, its value was found to be non-zero. Since we are yet to resolve the atmospheric mass square splitting problem, therefore, this lack of information leads to the existence of two mass orderings of neutrino, i.e. normal ordering (hierarchy): $m_1 << m_2 < m_3$ and inverted ordering (hierarchy): $m_3 << m_1 < m_2$. In addition to this, the upcoming experiments focuses in giving a precise value of θ_{23} and δ_{CP}. Though the absolute mass scale of neutrinos is yet to be confirmed, the Planck's experiment has been successful in giving the upper bound on the sum of the light neutrinos to be $\sum_{i=1}^{3} m_{\nu_i} < 0.12$ at a confidence level(CL) of 95%[6]. In Tab.(1.1), we present the allowed values of the neutrino oscillation parameter in the 3σ confidence level.

In todays scenario, there are numerous beyond Standard model (BSM) frameworks which tend to incorporate information on the neutrino masses and mixings. These extensions to the SM also provide a link between neutrino physics and cosmology. Some of the most favored BSM frameworks which are successful in addressing neutrino mass and provide a feasible explanation for dark matter(DM), baryon asymmetry of the Universe (BAU), neutrinoless double beta decay ($0\nu\beta\beta$), lepton flavor violation (LFV), etc are seesaw mechanisms[7–11], radiative seesaw mechanism[12–14], left-right symmetric model(LRSM)[15, 16]. On the other hand, existence of an extra flavor neutrino, known as sterile neutrino has been suggested by many experiments. This came into light due to the peculiarities in LSND[17, 18] and MiniBooNE[19–21] experiments. However, its exact mass scale and the number of its generation is yet to be known. Inspite of these shortcomings, sterile neutrino play a crucial role in physics beyond the SM. Based on its mass scale, it contributes to various sector of new physics such as cosmology[22–24], astrophysics[25, 26], collider physics[27–30] and many more. Another scheme wherein neutrino phenomenology and cosmology can be studied on the same footing is by introducing a scalar field to the extensions of SM. The scalar field plays a crucial role in generating the small neutrino mass, relic abundance and BAU concurrently. Such frameworks are widely discussed in the literature[13, 31–37]. This thesis includes two such frameworks which are extensions of the SM by a scalar doublet and right handed neutrinos.

Oscillation parameters	**bfp**$\pm1\sigma$	3σ**(NO)**	**bfp**$\pm1\sigma$	3σ**(IO)**
$\Delta m^2_{21}[10^{-5}eV^2]$	$7.42^{+0.21}_{-0.20}$	$6.82-8.04$	$7.42^{+0.21}_{-0.20}$	$6.82-8.04$
$\Delta m^2_{31}[10^{-3}eV^2]$	$2.515^{+0.028}_{-0.026}$	$2.435-2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.584-2.413$
$\sin^2\theta_{12}/10^{-1}$	$3.04^{+0.013}_{-0.012}$	$2.69-3.43$	$3.04^{+0.013}_{-0.012}$	$2.69-3.43$
$\sin^2\theta_{23}/10^{-1}$	$5.73^{+0.018}_{-0.023}$	$4.05-6.20$	$5.78^{+0.017}_{-0.021}$	$4.10-6.23$
$\sin^2\theta_{13}/10^{-2}$	$2.220^{+0.062}_{-0.063}$	$2.032-2.41$	$2.238^{+0.00064}_{-0.00062}$	$2.053-2.434$
$\delta_{CP}/^0$	194^{-25}_{+52}	$105-405$	287^{-32}_{+27}	$192-361$

Table 1.1 Latest Global fit 3σ values of neutrino oscillation parameters with best fit values[38].

1.1.2 Experimental developments:

Many phenomena beyond the scope of SM have been scrutinized by various experimental and observational set ups. However, more than half of them are yet to be confirmed through experimental evidences. To understand the anamolies of SM and deviations from its predictions, neutrino physics is believed to play a vital role, thereby a detailed understanding on it is of utmost importance. The approval of neutrino oscillation is a manifestation obtained from atmospheric-neutrino experiments (Kamiokande[39], Super-Kamiokande[40, 41], Soudan-2[42], MARCO[43]), solar-neutrino experiments(Homestake[44, 45], SAGE[46, 47], GALLEX[48, 49], Kamiokande[50], Super-Kamiokande[40, 41]) and accelerator LSND experiment[17, 51]. The existence of neutrino oscillation confirms the massiveness of neutrinos. Some other experiments which are committed in the favor of neutrino oscillation are SNO[52], K2K[53] and Fermilab-MINOS[274]. Though the signal for non-zero reactor mixing angle θ_{13} was first given by the long-baseline accelerator neutrino experiment Tokai-to-Kamioka(T2K)[54], however, its discovery was confirmed by the reactor experiments Daya Bay[55], reactor experiments for Neutrino Oscillations(RENO)[275] and Double

Chooz[56, 57]. Exploration of three-flavor effects are a consequence of the discovery of $\nu_\mu \rightarrow \nu_e$ appearance which was initially made by T2K[54] and later confirmed by NOνA experiment[58].

We know that many studies and experiments have provided a possibility for the existence of fourth flavor of neutrino. Though LEP data rules out this chance for the fourth state, but experiments such as LSND[17, 18] and MiniBooNE[19–21] provides a signal for the acceptance of this hypothetical neutrino. This extra flavor of neutrino, known as sterile neutrino has gained much importance in the recent years due to its ability of giving an insight about new physics and BSM predictions. Sterile neutrinos lying in the mass range of eV and keV can be perhaps detected in the future KATRIN experiments[59]. Also, a keV sterile neutrino holds a chance of affecting the electron energy spectrum in tritium β-decays[60]. Amongst its interesting characters, a sterile neutrino could serve the purpose of being a possible dark matter candidate. A keV sterile neutrino produced through collision and oscillation from active neutrino could be a probable DM constituent as proposed by Dodelson and Widrow[61]. Depending on its production mechanism and the mass range, a sterile neutrino can be a feebly interacting massive particle (FIMP) type of DM. Many constraints from Lyman-α[62], X-ray[63, 62] and structure formation[24] acts upon this kind of DM candidate to validate its phenomenology.

Though the SM is an uptight model which explains all possible physics behind the elementary particles, it still lags in addressing many phenomena in neutrino as well as cosmological sector. We will first introduce the SM followed by its shortcomings and then the physics beyond SM in the later sections.

1.2 Standard Model(SM)

One of the most well established models in particle physics which gives the theory for fundamental particles and their interactions is the Standard Model of particle physics. It consists of seventeen named particles with the latest particle being the Higgs Boson, discovered in 2012 at the Large Hadron Collider(LHC)[64]. Of all the ideas upon which the SM is built, the gauge principle is without any doubt the most important insight gained in quantum field theory which is represented as $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$[65]. In SM, the origin of charged lepton masses, quark masses along with the masses of W and Z bosons is explained via the Higgs mechanism. Using the idea developed by Peter Higgs, i.e. the Higgs mechanism, Salam and Weinberg built the original theory of Glashow to unify weak and electromagnetic interaction as electroweak interaction in 1964. The basic idea governing this theory is the Lagrangian density of the electroweak interaction with the consideration of massless vector bosons, electron and neutrinos. However, on introducing a Higgs field with non vanishing vacuum expectation value in the Lagrangian, a spontaneous symmetry breaking occurs in the Lagrangian density which further results in the generation of vector bosons and electron masses, but neutrinos and photons remain massless.

1.2.1 Particle interactions and their Lagrangian

The standard model consists of elementary particles which are categorised as fermions and bosons. Fermions are further classified into two sub-groups, i.e. leptons (e,μ,τ,ν_e,ν_e,ν_e) and quarks (u,d,c,s,t,b). Again bosons consists of gauge bosons namely 8 massless gluons, one massless photon and massive $W^{\pm}$, Z bosons. They are known as the force carriers that mediate the strong, electromagnetic and weak interactions respectively. Another constituent of bosons is the Higgs boson which is the latest addition to the SM. Quarks and leptons are considered to exist in three families and some compelling results from LEP point towards the existence of three neutrino flavors: electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). And interestingly quarks comes in three colors. Some of the properties of the particle content are as given in Table (1.2).

Particle(s)	**Content**	**Charge**	**Spin**	$\mathbf{SU(3)_C}$	$\mathbf{SU(2)_L}$	$\mathbf{U(1)_Y}$
Quarks	$(u,d)_L$	(2/3, -1/3)	1/2	3	2	1/3
(three generations)	u_R	2/3	1/2	$\bar{3}$	1	4/3
	d_R	-1/3	1/2	$\bar{3}$	1	-2/3
Leptons	$(\nu_e,e)_L$	(0,-1)	1/2	1	2	-1
(three generations)	e_R	-1	1/2	1	1	-2
Gluons	g	0	1	8	1	0
W bosons	$W^{\pm}$	± 1	1	1	3	0
Photon	γ	0	1	1	3	0
Z boson	Z^0	0	1	1	1	0
Higgs boson	H	0	0	1	2	1

Table 1.2 Particle content of the SM with their respective charge assignments under the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$. C in $SU(3)_C$ represents the color charge under this group, L in $SU(2)_L$ denotes the left-handedness and Y in $U(1)_Y$ is the hypercharge.

The complex scalar field of the SM, i.e. the Higgs field transforms as a doublet under $SU(2)_L$ and can be represented as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

where, the complex charged scalar part is $\phi^+ = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$ and $\phi^0 = \frac{\phi_3 + i\phi_4}{\sqrt{2}}$ is the neutral complex scalar field. The Lagrangian depicting the electroweak interactions and masses of the particles of the SM which is also symmetric under the group $SU(2)_L \otimes U(1)_Y$ is given by:

$$\mathcal{L}_{\mathcal{SM}} = \mathcal{L}_{Gauge} + \mathcal{L}_{Fermions} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}. \tag{1.1}$$

The kinetic term for the gauge fields of the SM can be given by the Lagrangian as follows:

$$\mathcal{L}_{Gauge} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{1}{4} W^i_{\mu\nu} G^{i,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}. \tag{1.2}$$

The gauge tensor fields in the above kinetic term are expressed as :

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_3 f^{abc} \tag{1.3}$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g_2 \varepsilon^{ijk} W^i_\mu W^k_\nu \tag{1.4}$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu . \tag{1.5}$$

The gluons are marked as $a \in [1,..,8]$, i corresponds to the three gauge fields of weak isospin and one gauge field linked to the weak hypercharge and ε^{ijk} is the structure constant of $SU(2)_L$ group. Again L corresponds to the family index of three generation of fermions. The kinetic energy term for fermions along with their interaction with gauge fields can be expressed in the Lagrangian as follows:

$$\mathcal{L}_{Fermion} = \sum_{\Psi_L} i\bar{\Psi}_L D_\mu \Psi_L + \sum_{\Psi_R} i\bar{\Psi}_R D_\mu \Psi_R . \tag{1.6}$$

We can further express the covariant derivative D_μ of the fermion gauge interaction by:

$$D_\mu \Psi_L = (\partial_\mu - ig_1 \frac{Y}{2} B_\mu - ig_2 T^i W^i_\mu)\Psi_L \tag{1.7}$$

$$D_\mu \Psi_R = (\partial_\mu - ig_1 \frac{Y}{2} B_\mu)\Psi_R \tag{1.8}$$

where, g_1 and g_2 represent the coupling constant of the group $U(1)_Y$ and $SU(2)_L$ respectively. T^i are the generators of $SU(2)_L$ group with i running from $1,2,3$ and Y denotes the hypercharge.

The gauge theory discussed is a theory of massless quanta, however, it is not acceptable as it shows a contrast with the experimental findings which confirms that fermions and three gauge bosons of weak interaction are massive. This can be overcomed by introducing a scalar field, i.e. the Higgs sector which imposes the electroweak symmetry breaking (EWSB). The

Lagrangian corresponding to the Higgs sector is given as:

$$\mathcal{L}_{Higgs} = (D^{\mu}\phi)^{*}(D_{\mu}\phi) + \mu^{2}\phi^{\dagger}\phi - \lambda(\phi^{\dagger}\phi)^{2}. \tag{1.9}$$

Here, the covariant derivative via which the Higgs field couples with the gauge field is expressed as:

$$D_{\mu}\phi = \partial_{\mu} - \frac{i}{2}g_{2}W_{\mu}^{i}T^{i} - i\frac{Y_{\phi}}{2}g_{1}B_{\mu} \tag{1.10}$$

with Y_{ϕ} denoting the hypercharge of the Higgs field. The Higgs doublet couples with the gauge field in order to break the symmetry $SU(2)_{L} \times U(1)_{Y}$. Now, we begin with the minimization of the Higgs potential so as to produce a non-zero vacuum expectation value (v) of the Higgs field for the condition $\lambda > 0$ and $\mu^{2} < 0$. The neutral part of the Higgs sector acquires the VEV and is given by:

$$<\phi>= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \tag{1.11}$$

where, v denotes the VEV $v = \sqrt{\frac{-\mu^{2}}{v}}$. In order to break the electroweak symmetry, an excitation around the ground state, i.e. the vacuum is considered which is written as:

$$<\phi>= \sqrt{\frac{1}{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \tag{1.12}$$

with h signifying the physical Higgs field. Now, the Lagrangian of the Higgs field given by Eq.(1.9) can be expressed in mass terms as:

$$\mathcal{L}_{Higgs} = M_{W}^{2}W_{\mu}^{+}W_{\mu}^{-} + \frac{1}{2}M_{Z}^{2}Z_{\mu}Z^{\mu} + \frac{1}{2}M_{h}^{2}h \tag{1.13}$$

where,

$$W^{+} = \frac{W_{\mu}^{1} - iW_{\mu}^{2}}{\sqrt{2}}, W^{-} = \frac{W_{\mu}^{1} + iW_{\mu}^{2}}{\sqrt{2}}, Z_{\mu} = cos\theta_{W}W_{\mu}^{3} - sin\theta_{W}B_{W}. \tag{1.14}$$

and

$$M_W = \frac{g_2 v}{2}, M_Z = \frac{g_2 v}{2cos\theta_W}, M_H = 2v\sqrt{\lambda}. \tag{1.15}$$

The Weinberg angle θ_W also known as the weak mixing angle can be expressed in terms of the coupling constants of the group $SU(2)_L$ and $U(1)_Y$ as follows:

$$\theta_W = cos^{-}(\frac{g_2}{\sqrt{g_1^2 + g_2^2}}). \tag{1.16}$$

However, due to non interaction of the photon with the Higgs field, it remains massless in the SM.

Similar to the mass generation of the gauge bosons, fermions also acquire mass through the Yukawa interaction which takes place between the scalar field and the fermioninc field. The gauge invariant Yukawa Lagrangian is given by:

$$\mathcal{L}_{Yukawa} = -Y_e \bar{L_L} \phi e_R - Y_u \bar{Q}_L \tilde{\phi} u_R - Y_d \bar{Q}_L \phi d_R \tag{1.17}$$

where $\tilde{\phi} = i\tau_2\phi^*$ and τ_2 is the Pauli spin matrix. The Yukawa couplings of the leptons, up quarks and down quarks are denoted by Y_e, Y_u and Y_d respectively. Thus, masses of the fermions can be obtained once the Higgs field acquire VEV (v). These masses can be expressed as follows:

$$M_e = Y_e v, M_u = Y_u v, M_d = Y_d v. \tag{1.18}$$

Neutrino interactions are precisely explained in the Standard Model(SM) by the virtue of the leptonic charged current and the leptonic neutral current. With the inclusion of free electrons, the amplitude of the neutron-electron scattering can be calculated at the lowest order in the weak interaction perturbation theory. However, due to non-existence of the right handed counter part of neutrinos in the SM, the Yukawa coupling term is forbidden and thus, neutrinos remain massless in SM.

1.2.2 Deficiencies of SM

The Standard Model (SM) of particle physics is an affluent and self-consistent one in the current scenario. However, it is not accountable in explaining various problems persisting in the Universe. Thus, it is considered inadequate in addressing many current experimental results. Inspite of the SM being the most admired model, it has to face many drawbacks and anamolies such as massiveness of neutrinos[66], baryon asymmetry of the universe (BAU) [67, 68], explaination for dark matter (DM)[69, 70], incorporation of gravity, also why gravity is so weak compared to electroweak or nuclear forces, etc. The SM lags in giving proper reason for the CP violation in weak interactions and at the same time if there can be any known valid justification for it being conserved in strong interactions. Thereby, considering all the unsolved problems in the SM, we need to extend it and go beyond it. We have addressed some of the unsolved phenomena of SM in the section below which are further extensively studied in our thesis.

1.3 Physics beyond Standard Model

1.3.1 Neutrino mass and mixing

1.3.1.1 Neutrino mass

As quoted by Ettore Majorana, the consideration of the Majorana neutrinos can be given an upper footing than Dirac's equation for neutral particles, as the former theory introduces smaller number of hypothetical entities.

Neutrino physics has evolved as an important branch in high energy physics due to the significance of neutrino mass in theoretical as well as experimental detection. As we know the existence of neutrinos was proposed by Pauli and then it was assumed that the neutrino mass is negligible or even massless. However, it has been now finally known that neutrinos are not massless. Since, there is no such evidence of the neutrinos, it is still an unsolved mystery. But prior knowledge suggests that it might be a possible manifestation of the SM at low-energy level.

A very over rated dilemma in Neutrino Physics is that whether neutrinos are Dirac or Majorana. We will further discuss the case of Dirac and Majorana neutrino mass in details:

Dirac mass: According to the conventional theory, neutrinos are treated as Dirac particles with spin 1/2. As discussed earlier, the mechanism responsible for the generation of masses of quarks and charged leptons, i.e. Higgs mechanism plays the same role in generating Dirac neutrino mass. Nevertheless, an extension with the help of three copies of right-handed neutrinos to the SM is required. We distinguish between the left-handed neutrinos of SM with the right-handed neutrinos by their participation in weak interactions. The newly added right-handed neutrinos are termed as `sterile` as they do not participate in weak interactions, on contrary to the active neutrinos i.e. the left-handed neutrinos. The charge assignment of the right-handed neutrinos under the symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ is given by $(1,1,0)$.

Majorana mass: The Dirac equation for a fermion field $\Psi = \Psi_L + \Psi_R$ is represented by:

$$i\gamma^{\mu}\partial_{\mu}\Psi_L = m\Psi_L \tag{1.19}$$

$$i\gamma^{\mu}\partial_{\mu}\Psi_R = m\Psi_R \tag{1.20}$$

where, the space-time evolution of the chiral fields Ψ_L and Ψ_R are coupled by the mass m. Thus, the explaination of a massless fermion can be very well given by a singlet chiral field be it left-handed or right-handed. Thus, it is possible to describe such physical entity with the help of Weyl spinors as represented in Weyl equation:

$$i\gamma^{\mu}\partial_{\mu}\Psi_L = 0 \tag{1.21}$$

$$i\gamma^{\mu}\partial_{\mu}\Psi_{R}=0 \tag{1.22}$$

This idea was discared by Pauli in 1933 as it lead to parity violation. But interestingly, in 1956-57, the discovery of parity violation proved Pauli's assumption to be invalid. Thus, the massless particles could be described with the help of Weyl spinor fields. Since there was no experimental evidence of the massive neutrinos, thus, they were represented with a left-handed Weyl spinor ν_L as proposed by Landau, Lee and Yang. As in the SM, neutrinos are massless, the description of it by left-handed spinors can be very well incorporated in the SM. However, the concept of four-component spinor for explaining the massive particles is not possible as discovered by Ettore Majorana. This anamoly could be thereby fixed by assuming the spinors Ψ_L and Ψ_R dependent on each other.

1.3.1.2 Neutrino Oscillation

Taking into account the mystery of the smallness of neutrino mass to be the most pressing aspect of the unsolved problems in SM, we see that Standard Model neither has any explaination for its massiveness nor forbids it from acquiring one. The discovery of Higgs Boson provides an insight to the electroweak symmetry breaking although the mass of the neutrinos remains difficult to be achieved. Discovery of neutrino oscillation experimentally and consecutively masses of neutrinos puts a light on the drawback of the SM, thereby compelling the study of new physics beyond the Standard Model (BSM). Neutrino oscillation is a quantum mechanical phenomenon, whereby a neutrino with a specific lepton family number (namely electron, muon and tau) can be measured to have different lepton family number. The probability of measuring a particular flavor for neutrinos varies between three known states, as it propagates through space. This very phenomenon also gives the most plausible solution of the solar neutrino problem, wherein the amount of flux observed experimentally is less than the flux that is to be observed theoretically. The mass eigen states and the flavor eigen states are related by a mixing matrix known as Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS).

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i, i = 1,2,3 \tag{1.23}$$

Here, ν_α denotes the flavor eigenstates of neutrino with $\alpha = e, \mu, \tau$ and ν_i represents the mass eigenstates of neutrino for $i = 1,2,3$. $U_{\alpha i}$ is the PMNS matrix and is actually a $(3+n_s) \times (3+n_s)$ unitary matrix, where, n_s is the number of sterile neutrinos. Thus, this matrix expressed as:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} P \tag{1.24}$$

where, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and $P = \mathrm{diag}(1, e^{i\alpha}, e^{i(\beta+\delta)})$. Here, δ is Dirac CP phase and α, β are the Majorana CP phases.

Neutrino oscillation in vacuum:

The neutrino oscillation phenomenon confers to the violation in the lepton number in neutrino propagation. A neutrino may change its flavor when it travels a distance L, i.e. a neutrino flavor originally ν_α evolves as follows:

$$|\nu_\alpha(t)>= \sum_{j=1}^{n} U^*_{\alpha j} |\nu_j(t)\rangle . \tag{1.25}$$

With the consideration of the neutrino as a plane wave $|\nu_j(t)\rangle = e^{-iE_jt} |\nu_j(0)\rangle$ and that neutrinos are relativistic such as:

$$E_j = \sqrt{p_j^2 + m_j^2} \simeq p + \frac{m_j^2}{2E} \tag{1.26}$$

Thus, the transition probability between ν_α and ν_β over a distance L is given by:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_{j=1}^{n} \sum_{k=1}^{n} U^*_{\alpha j} U_{\beta k} \langle \nu_k | \nu_j(t) \rangle \right|^2$$

$$\simeq \sum_{j,k} U^*_{\alpha j} U_{\beta k} U_{\alpha k} U^*_{\beta k} e^{-i\Delta m^2_{jk} \frac{L}{2E}} \quad (1.27)$$

where, $\Delta m^2_{jk} = m^2_j - m^2_k$. However, in case of two flavor mixing, the transition probability of a flavor ν_α having energy E_ν oscillating to ν_β after transversing a distance L can be expressed as:

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2 2\theta sin^2 (\frac{\Delta m^2 L}{4E_\nu}). \quad (1.28)$$

We can further rewrite the transition probability for the generic three neutrino families in terms of a CP conserving and a CP violating term :

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} Re[J^{\alpha\beta}_{ij}] sin^2(\frac{\Delta m^2_{ij} L}{4E_\nu}) \pm 2\sum_{i<j}^{n} Im[J^{\alpha\beta}_{ij}] sin^2(\frac{\Delta m^2_{ij} L}{2E_\nu}) \quad (1.29)$$

where, $J^{\alpha\beta}_{ij} = U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U^*_{\beta j}$. In case of neutrinos and antineutrinos the two terms have opposite signs.

Thus, it is evident from Eq.(1.28) that the transition probability is dependent on the mass square difference between the neutrinos and their mixing angle. Thus, for a non-vanishing probability, these entities must be non zero which further confirms that neutrinos must be massive.

Neutrino oscillation in matter:

As widely discussed, when a neutrino propagates in a medium, its properties tend to change on account of its interactions with the matter. The interactions vary with different flavors of neutrinos. Properties such as density and constituent of the medium are described by an effective potential, which further helps in explaining the effect of the medium. This effective potential corresponding to the evolution of ν_e in matter because of its charge current interactions can be written as:

$$V_C = \pm\sqrt{2}G_F n_e, \tag{1.30}$$

here, n_e denotes the number density of electrons and G_F is the Fermi constant. However, the charge current interactions that induces the effective potential for ν_μ and ν_τ is vanishing as muons and taus are absent in the medium. In case of neutral current interactions in a neutral medium, the effective potential corresponding to active neutrinos is given by:

$$V_N = \mp\frac{\sqrt{2}}{2}G_F n_n \tag{1.31}$$

where, n_n is the neutron number density. The effective potential due to the neutrino oscillation in a medium tends to modify the neutrino mass eigenstate and eigenvectors which further affects the flavor evolution. The effective mass thus takes the form:

$$M^2_{\nu e} = M^2_{\nu e} \pm 4EV_M \tag{1.32}$$

where,

$$V_M = \begin{pmatrix} V_e = V_C + V_N & 0 & 0 \\ 0 & V_\mu = V_N & 0 \\ 0 & 0 & V_\tau = V_N \end{pmatrix}. \tag{1.33}$$

The respective expressions for mixing angle and effective mass in a medium for two flavors are given as follows:

$$tan2\theta_M = \frac{\Delta m^2 sin2\theta}{\Delta m^2 cos2\theta - A} \tag{1.34}$$

and

$$m^2_{1,2}(x) = \frac{m_1^2 + m_2^2}{2} + E(V_\alpha + V_\beta) \mp (\sqrt{\Delta m^2 cos2\theta - A)^2 + (\Delta m^2 sin2\theta)^2}. \tag{1.35}$$

Thus, we can say that the mixing angle and the effective mass depends on the number density and neutrino energy. If the matter potential is constant or varies slowly, then the mass eigenstates act approximately as energy eigenstates and therefore forbids any mixing in the evolution. This is referred as the adiabatic transition approximation. Such conversion of adiabatic flavor neutrino in matter with varying density is explained by the Mikheyev Smirnov Wolfenstein (MSW) effect[281].

Neutrino oscillation is successful in determining the mass square difference of the neutrinos, nevertheless, the absolute mass of the neutrino remains unanswered. The two possibilities of neutrino masses are as follows:

• **Normal Hierarchy (NH):** This corresponds to the hierarchy pattern $m_1 < m_2 << m_3$. Here the solar neutrino oscillation is a manifestation of the lower levels, i.e $\Delta m_{23}^2 \equiv m_3^2 - m_2^2 > 0$ and $m_3 \simeq \sqrt{\Delta m_{23}^2}$.

• **Inverted Hierarchy (IH):** Here $m_1 \simeq m_2 >> m_3$, and the solar neutrino oscillation comes about due to the heavier levels, $\Delta m_{23}^2 = m_3^2 - m_2^2 < 0$.

1.3.1.3 Neutrino mass models

Neutrinos remain massless to all orders in perturbation theory as well as nonperturbatively in Standard Model as a consequence of its inability to comprise the mass term $\nu_{iL}^T C^{-1} \nu_{jL}$, where i and j are the generation indices and C is the Lorentz charge conjugation matrix. Since, the Lagrangian involved in SM strictly conserves lepton number and the term $\nu_{iL}^T C^{-1} \nu_{jL}$ violates the lepton number by two units, therefore, we are bound to extend the SM to incorporate this mass term which defines the massiveness of neutrinos. Amongst many beyond SM frameworks, seesaw mechanism is considered to be one of the most widely known formulism which can give adequate explanation of the anomalies persisting in SM. Seesaw mechanism has a criteria such that the lepton number must be violated at the high energy scale. Besides the seesaw mechanism, there are many other BSM frameworks including the neutrino two Higgs doublet model(ν2HDM)[71] which play crucial role in addressing various BSM phenomena. We will briefly discuss the seesaw mechanism which is further categorised into type I[7], type II[8], type III[9], inverse[10, 11] and radiative seesaw mechanism[12–14].

Type-I seesaw: In type-I seesaw mechanism, the Standard model is extended with the help of three right handed neutrinos(ν_R) with Majorana mass denoted by M_R. The generation of eV scale neutrino mass is a direct consequence of the newly added particle which has mass related to the grand unified theory (GUT) scale. The Lagrangian involving the neutrino mass is given by:

$$\mathcal{L}_{\text{typeI}} \supset \frac{1}{2}\begin{pmatrix}\bar{\nu}_L^C & \bar{\nu}_R\end{pmatrix} M_\nu \begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix} + h.c. \tag{1.36}$$

where, the light neutrino mass matrix is expressed as:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R. \end{pmatrix} \tag{1.37}$$

The Dirac mass term is given by $M_D = Yv/\sqrt{2}$, where Y corresponds to the Yukawa coupling between ν_R, SM lepton doublet L and Higgs doublet ϕ and v is the vev of ϕ. Further, on diagonalizing the mass matrix, we obtain two mass eigenvalues for $M_R >> M_D$ which are M_R and $m_\nu = -M_D.M_R^{-1}.M_D^T$.

Type-II seesaw: An additional $SU(2)_L$ triplet Higgs field to the SM is the main ingredient in type-II seesaw mechanism which is responsible for the generation of small neutrino mass. This Higgs triplet, $\Delta = (\Delta^{++}, \Delta^+, \Delta^0)$ has hypercharge 1 and can be expressed as:

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2}. \end{pmatrix} \tag{1.38}$$

The invariant Lagrangian for type-II seesaw is given by:

$$\mathcal{L}_{\text{typeII}} \supset (Y_\Delta L\Delta L + \mu\phi\Delta\phi + h.c.) + M_\Delta^2 \Delta^+ \Delta \tag{1.39}$$

where, the lepton number is broken as required by the theory due to Y_Δ and μ in the Lagrangian. On acquiring VEV by the neutral component of the Higgs triplet, $\Delta^0 = v_\Delta/\sqrt{2}$, the neutrino mass is generated which is thus, given by:

$$m_\nu = \frac{v_\Delta}{\sqrt{2}}. \tag{1.40}$$

Type-III seesaw: In type-III seesaw mechanism, a hyperchargeless triplet fermion, $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$ is added to the SM. This fermion triplet is expressed as:

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}. \tag{1.41}$$

The Lagrangian involving the neutrino mass is given by:

$$\mathcal{L}_{typeIII} \supset \frac{1}{2}\begin{pmatrix} \bar{\nu}_L^C & \bar{\Sigma}_R^0 \end{pmatrix} M_\nu \begin{pmatrix} \nu_L \\ \Sigma^{0c} \end{pmatrix} + h.c. \tag{1.42}$$

which is analogous to type-I seesaw except for the fermion triplet used instead of right handed neutrino. Here, M_ν takes the same form as in Eq. (1.37) on replacing M_R by M_Σ. Finally, the neutrino mass matrix is given by:

$$m_\nu \approx -M_D.M_\Sigma^{-1}.M_D^T \tag{1.43}$$

where, $M_D = \frac{Y_\Sigma v}{\sqrt{2}}$.

Inverse seesaw: It is an extension of the SM by a singlet fermion S and right-handed neutrino. In inverse seesaw, the lepton number is broken by a small variable which is guarded from radiative corrections. This results in considering TeV scale right-handed neutrino in contrast to type-I seesaw. We have the Lagrangian as follows:

$$\mathcal{L} \supset Y L\tilde{\phi}\nu_R + M_R \bar{\nu}_R^C S - \frac{1}{2}\mu_S \bar{S}^C S + h.c., \tag{1.44}$$

where μ_S is the lepton number violating symmetric mass matrix. In the basis (ν_L, ν_R^C, S^C), the mass matrix takes the form:

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_R^T \\ 0 & M_R & \mu_S \end{pmatrix} \tag{1.45}$$

where, M_R and μ_S are the mass matrices for right handed neutrinos and singlet fermion respectively. Diagonalization of the mass matrix is possible under the condition $\mu_S << M_D << M_R$. Thus, the light neutrino mass matrix is given by:

$$M_\nu = M_D M_R^{-1} \mu_S (M_R^T)^{-1} M_D^T. \tag{1.46}$$

Radiative seesaw: It is believed that the origin of neutrino mass is not similar to that of other particles which attain their masses via Higgs mechanism. Thus, radiative seesaw mechanism is considered to be one such beyond SM models which can explain the origin of neutrino mass. The contributions to neutrino mass is obtained from Feynman diagrams with one or more loop levels in case of radiative seesaw. Ernest Ma's scotogenic model[13, 201] is one of the popular models governed by the radiative seesaw mechanism wherein small neutrino mass generation at one loop level is achieved. Along with the radiative neutrino mass, it can also yield DM candidates. In this thesis, one of the models we explicitly study is the scotogenic model. It is an extension of the SM by three neutral singlet fermions N_k and a scalar doublet

$$\eta = \begin{pmatrix} \eta^\pm \\ \frac{1}{\sqrt{2}}(\eta_R^0 + i\eta_I^0) \end{pmatrix}. \tag{1.47}$$

Also the gauge group of the SM is extended by a discrete symmetry Z_2. Basically, the scotogenic model is based on the inert Higgs doublet model(IHDM)[72, 73, 34, 74, 75] and the IHDM is nothing but a minimal extension of the SM by a Higgs field which is a doublet under $SU(2)_L$ gauge symmetry with hypercharge $Y = 1$ and a built-in discrete Z_2 symmetry. The newly added particle content of the scotogenic model act as odd under the

Z_2 symmetry which implies that they have positive Z_2 parity whereas the SM particles are even and have negative parity. If the lightest component of this odd or inert Higgs doublet is electromagnetically neutral, it can be considered as a good DM candidate. Based on early findings on IHDM, two primary regions of DM mass has been shown in which the relic abundance can be produced: one below the W boson mass threshold ($M_{DM} < M_W$) while the other being around 500GeV or above. Due to strong bounds from direct detection experiments,the allowed DM masses in the low-mass regime is reduced to a narrow region near the resonance $M_{DM} \lessapprox \frac{m_h}{2}$. Whereas, in the high mass regime $M_{DM} \lessapprox 550$GeV, these limits are somewhat relaxed and thus, the direct production of DM at colliders will be suppressed compared to the low-mass regime. The two main rationale behind the extension of the IHDM are: to revive the intermediate regime of DM mass and to generate the light neutrino masses that remain unheeded in the pure IHDM. We have no Dirac mass term with ν and N, however, the similar Yukawa- like coupling involving η is allowed, nevertheless the scalar cannot get a VEV. The neutrino mass can be generated through a one-loop mechanism, which is based on the exchange of η partcile and heavy neutrino.

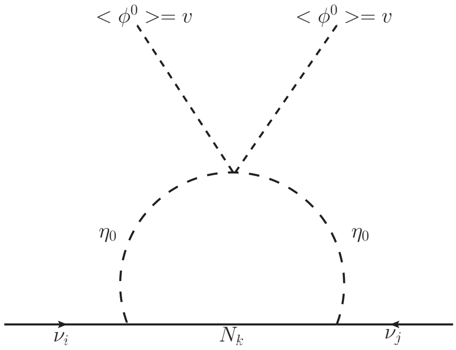

Fig. 1.1 Mass generation of light neutrino via one-loop contribution by the exchange of right handed neutrino N_k and the scalar η_0.

The lagrangian involving the new added field is :

$$L \supset \frac{1}{2}(M_N)_{ij}N_iN_j + Y_{ij}\bar{L}\tilde{\eta}N_j + h.c \tag{1.48}$$

where, the 1^{st} term is the Majorana mass term for the neutrino singlet and the 2^{nd} term is the Yukawa interactions of the lepton. The final mass matrix that can be obtained from the one loop Feynman diagram fig.(1.1) is represented as:

$$M_{ij}^{\nu} = \sum_k \frac{Y_{ik}Y_{jk}}{16\pi^2} M_k \left[\frac{m^2_{\eta^0_R}}{m^2_{\eta^0_R} - M_k^2} ln \frac{m^2_{\eta^0_R}}{M_k^2} - \frac{m^2_{\eta^0_I}}{m^2_{\eta^0_I} - M_k^2} ln \frac{m^2_{\eta^0_I}}{M_k^2} \right] \tag{1.49}$$

where, i and j are the generation indices, Y_{ik}, Y_{jk} denotes the Yukawa coupling matrix terms, M_k is the mass corresponding to N_k.

Neutrino two Higgs doublet model (ν2HDM): A lowscale energy framework is of much significance so as to validate the model with direct experimental tests. ν2HDM is one such low energy scale scenario by which we can explain small neutrino mass. It is an extension of the SM with the help of three heavy right handed singlet neutrinos (N_i, $i = 1,2,3$) and a scalar doublet (η). Here, mass of heavy right handed neutrino(M_N) can be considered of the order of 1 TeV, which means that the Dirac mass $M_D << 10^2$ GeV. Since, the light neutrino mass cannot be obtained via the SM Higgs doublet as it would distort the naturality, we introduce another scalar doublet which has a naturally small vacuum expectation value. The interesting phenomenon that is introduced in this model is, here, the heavy right handed neutrino N_i is assigned lepton number $L = 0$ instead of $L = 1$ to forbid the interaction term $N(\nu_L\phi^0 - l_L\phi^+)$. Further, the newly added scalar doublet is assigned $L = -1$, thus, resulting in the Lagrangian as:

$$\mathcal{L} \supset \frac{1}{2} M_{N_i} N_i^2 + y_{ij}\bar{N}_i(\nu_L\eta^0 - l_L\eta^+). \tag{1.50}$$

The effective mass matrix in case of ν2HDM therefore takes the form:

$$M_\nu = \sum_k \frac{y_{ik}y_{jk}u}{M_k} \tag{1.51}$$

where, M_k denotes the RHN mass for $k = 1,2,3$, u is the VEV of scalar doublet η and y_{ik}, y_{jk} are the elements of Yukawa coupling matrix.

1.3.2 Baryon Asymmetry of the Universe (BAU)

The baryon asymmetry of the Universe is another puzzle, which is the observed imbalance in the baryonic matter and anti-baryonic matter in the observable Universe. There are a set of conditions that were inspired by the recent discoveries of the cosmic microwave background [76] and CP violation in the neutral kaon system which are necessary for a baryon generating interaction to produce matter and antimatter at different rates. A particle to create baryon asymmetry, it must satisfy the Sakharov conditions[77], which demands baryon number (B) violation, C and CP violation, and departure from thermal equilibrium. As these conditions cannot be fulfilled within the SM in an adequate amount, we need formalism beyond the SM. Of these criteria, the out-of-equilibrium decay of a heavy particle leading to the generation of the baryon asymmetry of the Universe (BAU) has so far been a widely known mechanism for baryogenesis[78]. We can incorporate such a mechanism via leptogenesis[67], where a net leptonic asymmetry is generated first, which further gets converted into baryogenesis through $(B+L)$ violating electroweak sphaleron phase transitions[79]. A rich literature is available for various leptogenesis processes[80, 7, 81–84]. In the case of an elementary scenario, mostly referred to as vanilla leptogenesis, where the lower mass bound, by the allowance of flavor effect, comes down to be about $M_1^{min} = 10^8$ GeV [68, 85]. Owing to the fact that the CP asymmetry in RHN decays is a consequence of the active and sterile neutrino masses along with the necessity of tiny SM neutrino masses, the high mass scale of RHN is needed[86, 87]. However, such a high scale RHN may cause problems such as, it would decrease the possibility of detecting the dynamics of baryogenesis in the future collider experiments. Another problem which may arise as a result of heavy RHN is the naturalness problem[68]. Furthermore, high-scale leptogenesis may be very well discarded due to the detection of low-scale lepton number violation (LNV) in the near future. Thus, an alternative to the high-scale thermal leptogenesis can be obtained in case of scotogenic model where the mass of the RHN can be lowered upto 10 TeV[68].

1.3.2.1 Fundamentals for leptogenesis

We will discuss the case of thermal leptogenesis in scotogenic model and the applicable parameters which a play a crucial role in the generation of BAU. Some of the physical parameters such as decays and inverse decays of lightest of the RHN (N_1) along with their corresponding $\Delta L = 2$ washout processes have a significant role to play. However, the asymmetries produced by $N_{2,3}$ decays as well as the preexisting $B-L$ asymmetry is negligible due to strong washout effect by N_1 or $N_{2,3}$ itself. Thus, we are left with contributions coming from N_1 alone. An important condition that needs to be distinguished while carrying out our analysis on thermal leptogenesis is whether the washout regime is strong or weak. It is governed by the expression:

$$K_1 = \frac{\Gamma_1}{H(z=1)}, \tag{1.52}$$

where, Γ_1 is the total N_1 decay width, H is the Hubble parameter, $z = \frac{M_1}{T}$ and T is the temperature of the photon bath. The types of washout regime that can be categorised by eq.(1.52) is the weak washout regime corresponding to $K_1 \leq 1$, strong washout $K_1 \geq 4$[68] and an intermediate regime between them. Again, due to the effect of the washouts, a dilution factor (κ_1) comes into play. It can be parametrized for strong and weak washout regime respectively as given below:

$$\kappa_1 \simeq \frac{1}{1.2K_1[lnK_1]^{0.8}} \tag{1.53}$$

and

$$\kappa_1 \simeq \frac{1}{2\sqrt{K_1^2+9}}. \tag{1.54}$$

Another crucial ingredient of leptogenesis is the CP asymmetry ε_1 for the decays $N_1 \to l_L\eta, \bar{l}_L\eta^*$. The relation of the term will be discussed in details in the coming chapters. In eq.(1.52), the term Γ_1 represents the decay width which is given by:

$$\Gamma_1 = \frac{M_1}{8\pi}(Y^\dagger Y)_{11}\left[1-\left(\frac{m_{\eta_R^0}}{M_1}\right)^2\right]^2. \tag{1.55}$$

From eq.(1.55) it can be noted that the decay width is dependent on the elements of the Yukawa coupling matrix as well. Thus, it can be considered as another very important parameter in calculating the BAU. We arrive at the final baryon-to-photon ratio which is a product of the CP-asymmetry term with the dilution factor along with a conversion factor bearing a value $C \simeq 0.01$[282],

$$\eta_B = -C\varepsilon_1\kappa_1. \tag{1.56}$$

The experimental value given by Planck satellite for final baryon-to-photon ratio is $\eta_B = (6.1 \pm 0.18) \times 10^{-10}$.

1.3.3 Dark matter

Dark matter being the hot topic of discussion in cosmology, is said to occupy 27% of the present Universe on the basis of latest data from Planck satellite. The presence of Dark matter in the Universe is a manifestation of the discrepancy between the luminous mass and the gravitational mass. In order to measure the gravitational mass of the galaxy, or of a cluster of galaxy, one needs to study motion of the galaxy and incorporating the gravitational calculations we can estimate the gravitational mass required to keep a system bound. The significant lines of evidence of DM include observations in galaxy cluster by Fritz Zwicky[88] in 1933, gravitational lensing (which could allow galaxy cluster to act as gravitational lenses as postulated by Zwicky in 1937)[89], galaxy rotation curves in 1970[90], cosmic microwave background[76] and the most recent cosmology data given by Planck satellite[91] are some of the most remarkable ones.

Furthermore, on the basis of particle types, DM is sub-divided into Baryonic Dark Matter and Non-Baryonic Dark Matter. The existence of baryonic DM is considered since, the visible Universe cannot account for the baryon density in the Universe given by Planck data. The Big Bang Nucleosynthesis (BBN) gives a bound on baryonic density of the Universe, i.e. $\Omega_b h^2 = 0.02205 \pm 0.00028$. Baryonic dark matter might be inside Massive Astrophysical Halo Objects (MACHO), or small dense compact clouds having mass $\sim$ Jupiter ($\sim 10^{-3} M_0$). As they do not have any star to luminate them, they are not even radio loud. Some of the examples are: white dwarf, neutron star, black holes, brown dwarf etc. Whereas, the non-baryonic matter constitute most of the dark matter. Due to their weak interactions with ordinary matter, they are hard to detect and thus, masses are unknown. They are the relics of the Big Bang. The mass of the dark matter particle and the temperature of the Universe at the time of their decoupling determine whether the motion of the dark matter was relativistic or non-relativistic when they decoupled. Therefore, considering the mass and speed of dark matter, it can be divided into three types which are as follows:

Hot Dark Matter (HDM): When DM moves with a relativistic speed, it is termed as Hot Dark Matter. The mass of HDM being less ($m < T$) than their kinetic energies is a reason why HDM were extremely relativistic at the time of freeze-out. Neutrinos are popular candidate of HDM.

Cold Dark Matter (CDM): They are composed of heavy particles ($m > T$) and thereby, they remain non-relativistic at the freeze out time.

Warm Dark Matter (WDM): It is a kind of DM which falls in the intermediate state between a HDM and a CDM. Sterile neutrinos are one of its prominent candidate.

1.3.3.1 WIMP dark matter

Although, the nature of DM is not yet confirmed, by the knowledge of its cosmological and gravitational evidences, it can be categorised on the basis of its production, particle nature of its constituents and mass of DM particles. Considering the possible production, it is classified as Thermal Dark Matter and Non-Thermal Dark Matter. In case of thermal DM, it is considered to be produced via collision of the cosmic plasma in the radiation dominated era. When the DM were in thermal and chemical equilibrium in the early Universe, they were decoupled from universal plasma when the interaction rates became less than the expansion rate of the Universe and the comoving density of such particles became constant.

The Weakly Interacting Massive Particle (WIMP) can be considered as a probable DM candidate as it can be produced thermally by collision of the particles in thermal cosmic plasma. Therefore, the created particle-antiparticle pairs then could annihilate by the reverse reaction to form SM particles. Under the equilibrium condition, we have :

$$\eta_\chi - \bar{\eta}_\chi = 0 \tag{1.57}$$

Here, η_χ is the number density of the dark matter particle χ. For $T < m_\chi$, where m_χ is the mass of the dark matter particle χ.

$$\eta_\chi = \eta_\chi - \bar{\eta}_\chi \sim (\frac{m_\chi T}{2\pi})^{3/2} \exp^{\frac{-m_\chi}{T}} \tag{1.58}$$

Thus, the number density falls off as $\exp^{\frac{-m_\chi}{T}}$ because the tail part of the above equation can only provide kinetic energy for particle-antiparticle collision to produce WIMP pairs. As mentioned earlier, for the comoving volume to become constant, the annihilation rate must fall just below the expansion rate. This is known as Freeze-out of the species from when they flow as a relic. Thus, now the relic density becomes dependent on the annihilation cross-section as:

$$\Omega_\chi \sim \frac{1}{< \sigma v >} \tag{1.59}$$

Ω_χ is the density of dark matter normalized to the critical density of the Universe and it is the solution of Boltzmann equation which is given by:

$$\frac{dn_\chi}{dt} = -3H\eta_\chi - (<\sigma v>)(\eta_\chi^2 - (\eta_\chi^2)_{eq}) \tag{1.60}$$

The 1^{st} term of right hand side of the equation shows the dilution of dark matter χ due to the expansion of the Universe and the 2^{nd} and 3^{rd} term are the pair production and pair annihilation of χ respectively.

A notable co-occurrence frequently termed as the WIMP miracle[92] is feasible in the WIMP paradigm, where a dark matter candidate typically with an electroweak scale mass and electroweak alike interactions can produce correct dark matter relic abundance. WIMPs can be thermally produced in the early Universe as the interactions governing them are of electroweak scale. Thus, relic abundance of a thermal DM candidate can be generated while the interactions freeze out, ensuing the expansion as well as the cooling of the Universe. Also, the WIMP paradigm foretells the observable DM nucleon scattering cross-section through the same interactions that were operational at the time of freeze-out. However, many dark matter direct detection experiments like LUX[93], PandaX-II[94], and XENON1T[95] have reported their null results. Therefore, the exclusion curve in the mass-cross section plane is lowered. Similar null results have been obtained from the Large Hadron Collider (LHC), which further gives an upper bound on the DM interaction with the SM particles. A strict constraint on the WIMP parameter space can be summarized from the different null results.

Now, coming to Non-Thermal Dark Matter, we can assume that the dark matter particles never experienced chemical or thermal equilibrium since, the cosmic history begore the Big Bang Nucleosynthesis (BBN) is not known with confidence. Dark matter particles can be produced through through the process of gravitational particle production wherein the particles are produced due to expansion of the Universe. They can have large mass of $\sim$ few hundreds GeV (10^{13} GeV or higher) than the WIMP's, eg: WIMPZILLA's. They can be produced at the preheating or during the reheating stage after the inflation. Non-thermal production of dark matter may also be realized by late decays of scalar field. Such decays may be due to the renormalization interactions, which will lead to SM particles, unless the interaction is considerably weak. And this kind of decay of long-lived particles can also non-thermally produce a candidate for DM, namely wino. For "wino" to be a DM candidate, its mass should be $\sim 2-3$ TeV. But in case of non-thermal production of wino, the non-thermal candidate for DM with smaller wino mass is also possible.

When a CDM WIMP scatters off a detector nuclei in principle , and in case any signature corresponding to it is observed, then this will lead to what is termed as direct detection. If a terristrial DM detector is encountered by DM then due to the impact, the DM will scatter off the nucleus of the detector material which results in recoiling of the detector nucleus. The scattering is an elastic one with very weak interaction strength. The recoil energy of the nucleus will be very low ($\sim$ keV). Therefore, the loss in energy of the recoiling nucleus is detected by the effect it may produce in the detector in the form of scintillator light, bolometric current, photon excitation, ionization etc. If one can detect or obtain the directionality of the recoil nucleus, it will give not only the signature of the dark matter event in the detector but also enable one to extract the dark matter mass and scattering cross-section.

1.3.3.2 FIMP dark matter

There exists another formulism for the calculation of dark matter genesis, i.e. "thermal freeze-in". In this mechanism, the probable dark matter candidate involves a Feebly Interacting Massive Particle (FIMP) which interacts so feebly with the thermal bath that it never attains thermal equilibrium. Freeze-in mechanism in just the opposite to freeze-out mechanism discussed in the previous subsection. Freeze-in can also be considered as an alternate mechanism which is IR dominated by low temperatures near the DM mass and is independent of the unknown UV physics which includes reheating after inflation. On increasing the interaction strength, the production from the thermal bath also increases, however, the initial DM abundance in freeze-in is negligible.

1.3.3.3 keV sterile neutrino: another probable DM candidate

The existence of sterile neutrino is yet another manifestation of physics beyond the SM. They transform as singlet under the gauge group $SU(2)_L \times U(1)_Y$. The mixing between the active and sterile neutrino is a manifestation for the existence of sterile neutrinos[96]. There are many models constructed by extending the SM by one or more sterile neutrinos to explain the DM phenomenology along with active-sterile mixing[97, 98]. Sterile neutrinos in eV range could show lines of evidence in weak decay spectra like in β decay[99–103]. Also heavier sterile neutrinos, i.e in TeV range might have remarkable affect on the neutrinoless double beta decay($0\nu\beta\beta$)[104]. Whereas, keV scale sterile neutrino play an important role in the field of cosmology depicting it to be a probable DM candidate. Since they are chargeless, massive and have a very long lifetime, they could serve the criteria to be a DM candidate. Sterile neutrinos could be a warm or cold dark matter governed by its production mechanism. The elementary mechanism of its production is via the mixing of active-sterile neutrinos in the primordial plasma. Sterile neutrino if considered a DM candidate, one thing is assured that it cannot be a thermal relic. This is a consequence of the fact that it surpasses the critical density of the Universe, $\rho_c = 10.5h^2 keV/cm^3$. As the relic abundance of sterile neutrino DM is related to its mass and mixing angle, thus, depending on its mixing the production mechanism can be classified as resonant[105–108] and non-resonant[109]. The resonant production of DM intensifies on basis of the lepton asymmetry existing in the plasma, meanwhile, the non-resonant production can be interpreted as a production of very small amount of DM abundance for a given DM mass and mixing[110]. Since, the sterile neutrinos are fermions, they are bound to satisfy the Tremaine-Gunn limit[111]. And to contribute 100% to the DM abundance, the mass of sterile neutrino must be above 0.4 keV.

There are several bounds on keV sterile neutrino from various experiments and cosmological observation. A much stronger bound on the mixing angle comes from a one loop decay $N \rightarrow \nu + \gamma$, which guides to a monochromatic X-ray line signal. Further, in order to produce the desired relic abundance, the mass of sterile neutrino must lie below 50 keV[107, 112]. Thus, roughly it can be said that the preferable mass range for sterile neutrino must lie in between $0.4 - 50$ keV to behave as a DM candidate. However, much stronger bounds may be derived from the structure formation data relying on the production mechanism.

1.3.4 Neutrinoless double beta decay($0\nu\beta\beta$)

Taking into account the Majorana nature of the neutrinos, neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most promising processes. It is a lepton number violating process which if observed will prove the Majorana nature of the neutrinos. Extending the picture from the SM to Grand Unified Theories (GUTs), quarks and leptons live together in multiplets, and hence both B and L are not expected to be conserved quantities. The combination of $B - L$, which is conserved in the SM both at the classical and quantum level, often plays an important role in GUTs, and is broken at some stage. $0\nu\beta\beta$ would also violate the $B - L$ quantity which would further have significant implications in the theories which are trying to explain the matter anti-matter asymmetry of the Universe. It being a radioactive decay transforms a nuclei of atomic number Z to its isobar with atomic number $Z + 2$,

$$(A,Z) \longrightarrow (A,Z+2) + 2e^- \tag{1.61}$$

thereby violating the lepton number. The observable of $0\nu\beta\beta$ is its time period which is given by:

$$\frac{\Gamma_{0\nu\beta\beta}}{ln2} = G \mid \frac{M_\nu}{m_e} \mid^2 \mid m_{\beta\beta} \mid^2 \tag{1.62}$$

where G contains the phase-space factors, m_e is the electron mass and M_ν is the nuclear matrix element. Some of the experiments which gives the most robust bounds on life time of $0\nu\beta\beta$ are KamLAND-ZEN[113, 114], GERDA[115, 116], CUORE[283] AND EXO-200[284]. The effective neutrino mass that appears in eq.(1.62) for time period is given by,

$$m_{\beta\beta} = \sum_{k=1}^{3} m_k |U_{ek}|^2 \tag{1.63}$$

where, U_{ek}^2 are the elements of the neutrino mixing matrix with k holding up the generation index. This eq.(1.63) can be further expressed as,

$$m_{\beta\beta} = m_1|U_{ee}|^2 + m_2|U_{e\mu}|^2 + m_3|U_{e\tau}|^2. \tag{1.64}$$

Again, if we introduce an additional sterile fermion S to the SM, then the decay amplitude will be modified resulting in the correction of the effective mass as[285],

$$m_{\beta\beta} = \sum_{k=1}^{3+S} U_{ek}^2 p^2 \frac{m_k}{p^2 - m_k^2}, \tag{1.65}$$

where, U_{ek} is the mixing matrix including the extra active-sterile mixing elements and $p^2 = -(125)\text{MeV}^2$ denotes the virtual momentum of neutrino. Therefore, the modified effective mass expression after incorporating the extra sterile field is of the form[286]:

$$m_{\beta\beta}^{3+S} = m_{\beta\beta} + m_4|\theta_S|^2, \tag{1.66}$$

here, m_4 is the mass of sterile fermion and θ_4 is the active-sterile mixing element. Some stringent upper bounds on effective mass $m_{\beta\beta}$ with CL 90% comes from experiments such as KamLAND-ZEN and GERDA, viz. $m_{\beta\beta} < 0.061 - 0.165$eV. Though there are no firm confirmations from experiments which can prove the $0\nu\beta\beta$ process, however, many ongoing and future experiments[287, 288] tends to provide more accurate bounds on the effective mass in the years to come.

1.3.5 Lepton flavor violation (LFV)

The neutrinos remain massless in the SM and three generations of fermions are placed in the form of discrete doublets. This leads to the disallowance of Lepton Flavor Violating processes involving the charged leptons in the minimal SM. But interestingly, there are a number of neutrino experiments namely, reactor[117–119, 55, 120, 121], atmospheric[122–125], solar[126, 52, 127–130, 47, 131–133] experiments that yields the result that LFV processes do take place. This opens up a window for the charged leptons as well, thereby expecting the LFV processes to be observed in them. However, these processes are so tiny and suppressed that it may lie beyond the experimental reach. Thus, the observation of LFV processes provides a vivid picture of the existence for physics beyond the SM. There are many ongoing experiments which searches for lepton flavor violating decay of two body($l_k \to l_i\gamma$) and three body decay($l_k \to l_i l_j l_j$). The search for radiative muonic two body decay, $\mu \to e\gamma$ has been carried out since 1940's and the recent constraints on its value is given by the MEG collaboration[134–137]. The best bound in case of the three body decay, $\mu \to eee$, comes from the SINDRUM II experiment[138]. However, the bound on $\mu \to eee$ decay is expected to be more precise in the future by the Mu3e collaboration[139]. A list of the LFV processes with their present and future sensitivity is shown in table.(1.3). Besides these decays, a muonic atom may undergo a muon-electron conversion. Various experiments focussing on the muon-electron conversion(CR($\mu \to e$)), such as DeeMe[140], Mu2e[141, 142], COMET[143] targets on reaching a sensitivity of 10^{-14}, 3×10^{-15} and $10^{-15(-17)}$ respectively. Another possible decay of the muonic atom is its decay into a pair

LFV Process	Present bound	Future sensitivity
$\mu \to e\gamma$	5.7×10^{-13}[137]	6×10^{-14}[148]
$\mu \to 3e$	1.0×10^{-12}[149]	$\sim 10^{-16}$[150]
$\tau \to e\gamma$	3.3×10^{-8}[151]	$\sim 10^{-8}-10^{-9}$[152]
$\tau \to \mu\gamma$	4.4×10^{-8}[151]	$\sim 10^{-8}-10^{-9}$[152]
$\tau \to 3e$	2.7×10^{-8}[153]	$\sim 10^{-9}-10^{-10}$[152]
$\tau \to 3\mu$	2.1×10^{-8}[153]	$\sim 10^{-9}-10^{-10}$[152]
$\mu^-, Au \to e^-, Au$	7.0×10^{-13}[154]	-
$\mu^-, Ti \to e^-, Ti$	4.3×10^{-12}[155]	$\sim 10^{-18}$[156]

Table 1.3 Present and future bounds by various experiments on low-energy scale LFV processes.

of electrons, $\mu^- e^- \to e^- e^-$[144, 145]. Though there are no experimental evidences on this decay, it is expected to be studied at COMET and Mu2e in the near future. In case of τ decay channels, the bounds are not very robust, however, commendable developments are anticipated at B factories[146, 147].

1.4 Discrete flavor symmetry

Particle physics and symmetries display a significant relation in explaining various phenomena persisting in the Universe. In order to understand the different kinds of interactions between particles, such as weak, electromagnetic and strong interactions, continuous symmetries like Lorentz, Poincare and gauge play a vital role. Similarly, discrete symmetries such as Charge conjugation (C), Parity (P) and Time reversal (T) are also significantly useful in particle physics.

In case of beyond standard model frameworks, Abelian discrete symmetries, Z_N are of much importance in order to constrain the couplings in the model. Furthermore, non-Abelian discrete symmetries like A_N[157–170], S_N[171–184, 184–187], D_N[188–192], T'[193–197], etc are also a useful tool in model building of particle physics, specifically in getting a wider idea about flavor physics. Thus, such kind of symmetries are also termed as flavor symmetries and are thereby introduced in models to control the Yukawa couplings within the three generations of quarks and leptons. As we know that the neutrinos remain massless in the SM, therefore implementing flavor symmetries in extensions of SM helps us in explaining the neutrino masses and mixings. One of the salient features of non-Abelian discrete symmetries in model building is to obtain the experimental values of lepton and quark masses and mixing angles. These symmetries may have originated from higher dimensional space-time symmetries. There are a number of models in particle physics wherein discrete symmetries (such as A_4, S_4, Z_4, etc) are used to predict the mixings and masses of active neutrinos and check its compatibility with the experimental datas.

In the following subsections, we will briefly discuss the discrete symmetries used in the construction of our models based on which we have carried out our work in this thesis.

1.4.1 Z_N: Abelian discrete symmetry

As mentioned earlier, Z_N group falls under the Abelian discrete symmetry group. It demonstrates a plane figure bearing a symmetry which is invariant after a rotation of $\frac{2\pi}{n}$. Z_2 is the simplest non-trivial group constituing of two elements e, σ, such that $e\sigma = \sigma e = \sigma, \sigma^2 = \sigma\sigma = e$. In simple words, we can say that Z_2 consists of +1 and -1 and under this symmetry, a field (say y) transforms as $y \to -y$. On the other hand, the group elements of Z_3 and Z_4 are $(1, \omega, \omega^2)$ and $(1, -1, i, -i)$ with a representation given by triangular and square symmetry respectively.

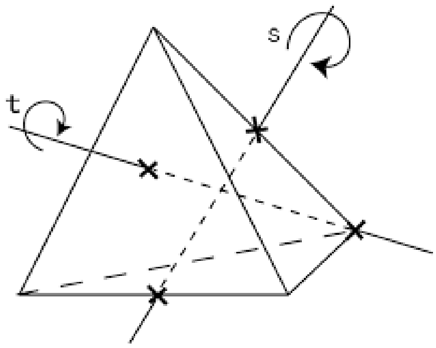

Fig. 1.2 A_4 symmetry as a tetrahedron.[198]

1.4.2 A_4: Non-Abelian discrete symmetry

A_4 is a group comprising of all even permutations among S_4 and is of the order $\frac{(4!)}{2}$[198]. It is also known as the alternating group. As shown in fig.(1.2), A_4 group is the symmetry of a tetrahedron. It has 12 group elements and four irreducible representations: 1, $1^{'}$, $1^{''}$ and 3. The two permutations which can generate A_4 group are namely S and T. The repeatative multiplication of the two generators, $S = (14)(23)$ and $T = (123)$ gives rise to the 12 elements of this group. Also their irreducible representations are different from each other. There are 12 even permutations which can be obtained from S and T:

$$
\begin{aligned}
I =&(1234)\\
T =&(2314), ST = (4132), TS = (3241), STS = (1423)\\
T^2 =&(314), ST^2 = (4213), T^2S = (2431), TST = (1342)\\
S =&(4321), T^2ST = (3412), TST^2 = (2143).
\end{aligned}
\tag{1.67}
$$

The three one dimensional and one three dimensional irreducible representation can be obtained as follows:

$$\begin{array}{lll} 1 & S=1 & T=1 \\ 1^{'} & S=1 & T=e^{i\pi/3}\equiv\omega \\ 1^{''} & S=1 & T=e^{i4\pi/3}\equiv\omega^2. \end{array} \tag{1.68}$$

In case of a three dimensional representation, we consider a basis in which S is diagonal, which yields the generators as follows:

$$S=\begin{pmatrix}1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{pmatrix},\quad T=\begin{pmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\end{pmatrix}. \tag{1.69}$$

However, in our work as the charged lepton mass matrix is a diagonal one, therefore, we consider the basis in which T is diagonal. The main requirement to be known for building an A_4 invariant Lagrangian is the Clebsch-Gordan decomposition of direct products into irreducible representation. It can be obatined from the characteristic table as follows:

$$1\otimes 1=1,\quad 1^{'}\otimes 1^{''}=1,\quad 1^{'}\otimes 1^{'}=1^{''},\quad 1^{''}\otimes 1^{''}=1^{'}, \tag{1.70}$$

$$3\otimes 3=1\oplus 1^{'}\oplus 1^{''}\oplus 3_a\oplus 3_s. \tag{1.71}$$

Here, the subscripts a and s denote the asymmetric and symmetric term respectively. The direct product of two triplets namely (a_1,b_1,c_1) and (a_2,b_2,c_2) can be decomposed into the direct sum as,

$$\begin{aligned} &1\sim a_1a_2+b_1c_2+c_1b_2,\quad 1^{'}\sim c_1c_2+a_1b_2+b_1a_2,\quad 1^{''}\sim b_1b_2+c_1a_2+a_1c_2,\\ &3_a\sim(b_1c_2-c_1b_2,a_1b_2-b_1a_2,c_1a_2-a_1c_2),\\ &3_s\sim(2a_1a_2-b_1c_2-c_1b_2,2c_1c_2-a_1b_2-b_1a_2,2b_1b_2-a_1c_2-c_1a_2). \end{aligned} \tag{1.72}$$

Furthermore, on consideration of the two triplets as (a_1, a_2, a_3) and (b_1, b_2, b_3), their direct product is decomposed as follows:

$$\begin{aligned} 1 &\sim a_1b_1 + a_2b_3 + a_3b_2, \quad 1^{'} \sim a_3b_3 + a_1b_2 + a_2b_1, \quad 1^{''} \sim a_2b_2 + a_1b_3 + a_3b_1, \\ 3_a &\sim (a_2b_3 - a_3b_2, a_1b_2 - a_2b_1, a_1b_3 - a_3b_1), \\ 3_s &\sim (2a_1b_1 - a_2b_3 - a_3b_2, 2a_3b_3 - a_1b_2 - a_2b_1, 2a_2b_2 - a_1b_3 - a_3b_1). \end{aligned} \tag{1.73}$$

1.5 Outline of the thesis

The thesis is organized in the following manner:

Chapter 1 includes the introductory part of the thesis. Here, we have begun with the origin of neurinos and their theoretical and experimental advancements. Further, we discuss the SM and its shortcomings. In the later half of this section, we briefly present the beyond SM frameworks including the seesaw mechanism (type-I, type-II, type-III, inverse), scotogenic model and neutrino two Higgs doublet model. We also address some of the BSM phenomena such as neutrino mass and mixing, baryon asymmetry of the Universe, dark matter, neutrinoless double beta decay and lepton flavor violating processes. Lastly, we discuss about the discrete flavor symmetries and its impact on neutrino physics. Some important properties of Abelian discrete symmetry (Z_N) and non-Abelian discrete symmetry (A_4) are also discussed in this part.

In **Chapter 2**, a minimal scotogenic model is discussed in details. Here, the neutrino mass is generated by virtue of the inert scalar doublet and simultaneously the lightest of this scalar doublet serves as a probable dark matter candidate. We also study baryon asymmetry of the Universe which is a consequence of the decay of next to lightest right handed neutrino N_2 in our case. Thermal and non-thermal production of relic abundance is also analysed in details. Further, we also check the viability of the model w.r.t the constraints arising from $0\nu\beta\beta$ and LFV processes.

Chapter 3 includes the flavor symmetric realization of the scotogenic model with the help of discrete symmetric group $A_4 \times Z_4$. By incorporating this flavor symmetry and by appropriately choosing the vacuum expectation value alignment we are able to construct three structures of one zero texture Yukawa coupling matrix. Among the three structures, only one complies with the $\mu - \tau$ asymmetric condition. Therefore, we discard two structures of Yukawa coupling matrix and carry out our phenomenological analysis on just one. We study phenomena such as BAU, $0\nu\beta\beta$, dark matter and LFV processes.

In **Chapter 4**, we introduce another model which is the neutrino two Higgs doublet model (ν2HDM) and implement discrete flavor symmetry to realize it. In this work, we emphasis our analysis on the dark matter sector and try to link it with the neutrino phenomenology and BAU with the help of a decay parameter. We basically study a FIMP type of dark matter in this model by extending it by a dark sector. Thus, we successfully correlate the phenomena carried out in the analysis and confirm the viability of our model.

Chapter 5 is the study of ν2HDM wherein we have added an extra fermionic field. The additional particle is termed as sterile neutrino which plays a crucial role is defining the active neutrino sector and dark matter phenomenology. In this work, we have considered the sterile neutrino to be a probable dark matter candidate. The active-sterile mixing angle produced in this model has a vital part in generating the relic abundance and decay rate of DM. Also, $0\nu\beta\beta$ and BAU are also studied within this framework. We incorporate constraints from KamLAND-ZEN to see if the value of effective mass produced is feasible with the experimental limit. Also, in order to have a strong footing on the DM candidate, we include constraints from Lyman-α, X-ray and structure formation.

Finally, we draw the conclusions from all the above chapters and present it in **Chapter 6**.