Abstract

With the discovery of the Higgs particle at the LHC experiments in 2012, a very important revolution was marked in the field of particle physics [1]. This discovery, apart from providing the missing piece to the Standard Model (SM), paved the way for a better understanding of the fundamental particles and elegantly explained the processes responsible for generating the masses of quarks and leptons through Higgs mechanism. The different kinds of interactions which are present in Standard Model are governed by the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. These groups refer to strong, weak and electromagnetic interactions of the fundamental particles. Like many other good things, despite its grand success, the SM has a series of limitations that need careful considerations. Though the SM incorporates three of the fundamental forces, it fails to include the gravitational interaction. There is no proper justification as to why the gravitational force is very weak as compared to electroweak or nuclear forces. Moreover, there are many challenging issues in cosmology, astrophysics, particle physics etc. which are still not addressed and the answers to these phenomena are yet to be found. Some of these prominent challenges are neutrino oscillations and generation of their tiny masses, lepton number violating processes (LNV), baryon asymmetry of the universe (BAU), dark matter, dark energy etc. These cosmological observations are out of reach of the Standard Model. Eventually these limitations gave birth to the concept of Beyond the Standard Model (BSM) frameworks. At present times, people strongly believe that a proper understanding with a suitable explanation of these challenging issues can be found in this BSM paradigm.

SM contains three generations of neutral fermions i.e. electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). These neutrinos, being very weakly

interacting particles, are extremely difficult to detect despite the fact that trillions of them pass through our bodies in every second. The discovery of neutrino oscillation by the famous Super-Kamiokande experiment in 1998 confirmed that neutrinos should be massive in nature [2, 3]. The results of this experiment also highlighted the need for mixing between different generations of neutrinos for successful oscillation among the three flavors. The parameters that govern neutrino physics include three mixing angles: θ_{12}, θ_{13}, θ_{23} and two mass-squared differences: solar and atmospheric mass-squared differences. Though the experiments, such as MINOS [4], RENO [5], T2K [6], Double-Chooz [7] etc. have accurately measured the values of these parameters, there are still some uncertainties regarding CP violation, absolute mass of each neutrinos, mass hierarchies.

The need for frameworks Beyond the Standard Model has become increasingly popular to address its anomalies. Some of these BSM frameworks include the seesaw mechanism [8], radiative seesaw [9], inverse seesaw [10], minimal inverse seesaw [11] and many others. The seesaw mechanism, in particluar, is a compelling formalism for generating tiny neutrino masses. It predicts the existence of two types of neurino handedness: the SM left-handed neutrino and a hypothetical right-handed neutrino. In this framework, mass of the right-handed neutrino is significantly higher compared to the SM left-handed neutrino. Another popular mechanism is the inverse seesaw which contains right-handed neutrinos and sterile fermions as additional particles. This mechanism is capable of lowering the energy scale of right-handed neutrinos to TeV, thereby, enhancing the possibility of their detection in the ongoing experiments. In this thesis, we have performed our study in minimal inverse seesaw, ISS(2,3). This is a minimal version of the conventional inverse seesaw, which contains two right-handed neutrinos and three gauge singlet sterile fermions.

Group theory serves as a very important tool for mathematical interpretation of the processes and interactions observed in particle physics. In particular, discrete symmetry groups such as A_4, S_4, Z_N and modular groups $\Gamma(N)$ play a crucial role in neutrino physics model building [12, 13]. In this thesis we have done most of the work in ISS(2,3) framework by using finite modular group $\Gamma(3)$, which is isomorphic to non-abelian discrete symmetry group A_4 [14]. This approach explains the generation of tiny masses of neutrinos without requiring an excessive number of flavons. Apart from these edges, the models built through this approach are able to determine the parameters that define baryon asymmetry, dark matter, lepton number violation, lepton flavor violation etc. Thus, we can evaluate the validity and predictive power of our models. In the following paragraphs, we briefly discuss these BSM cosmological phenomena which are relevant to this thesis.

The world we observe around us is matter dominated. Several cosmological observations and findings hint towards the existence of an inequality between matter and anti-matter in the universe. This difference between matter (baryons) and anti-matter (anti-baryons) is termed as baryon asymmetry of the universe (BAU). It was Sakharov who proposed a theory that could generate this asymmetry through a dynamical process called baryogenesis [15]. According to him, there are three important ingredients that must be fulfilled for a successful explanation of baryon asymmetry; Baryon number violation, C and CP violation, out-of-equilibrium decays. One of the ways to achieve this asymmetry is through out of equilibrium decays of heavy fermions, such as right-handed neutrinos. This method, known as leptogenesis, creates an asymmetry in leptonic sector which is eventually converted into baryon asymmetry through sphaleron processes [16]. In ISS(2,3) decay of a quasi-Dirac pair which are formed by heavy right-handed and sterile fermions contribute to this asymmetry. Moreover, this framework is able to produce low scale leptogenesis.

Neutrinoless double beta decay is an important nuclear reaction which holds the answer to many of the pressing questions in particle physics. It is a radioactive decay process through which a nucleus of atomic number Z gets converted into a daughter nucleus of atomic number $Z + 2$. This lepton number violating decay is characterised by its life-time and effective Majorana mass of electron neutrino which are being actively searched for in experiments, such as KamLAND-Zen

[17], GERDA [18], CUORE [19] etc. This nuclear decay is closely linked to the nature of neutrinos, specifically whether they exhibit Dirac or Majorana characteristics. Notably, this reaction is more strongly associated with Majarona nature of neutrinos and a possible detection will confirm the same for neutrinos.

One of the hot topics in cosmology is the presence of dark matter. As per the latest observations from Planck satellite, about 26% of matter-energy distribution of the universe is composed of this non-luminous, non-baryonic, neutral and non-radiative form of matter [20]. The existence of dark matter exhibits a possible inconsistency between luminous mass and gravitational mass of the universe. Some of the prominent evidences for the presence of dark matter include the observations of galaxy clusters by Fritz Zwicky, behavioral study of galaxy rotation curves, effect of gravitational lensing due to large massive clusters and various observations from the Planck satellites. Based on these evidences, DM can be classified with respect to its mass, possible production channels, ability to form large scale structures, nature of the particles etc. Accordingly we have Thermal dark matter, Non-Thermal dark matter, FIMP (Feebly Interacting Massive Particles), WIMP (Weakly Interacting Massive Particles) etc. In our work we have considered a scalar type of dark matter and tried to check its compatibility with recent data from various cosmological observations.

The topics discussed above provide the motivation for the works done in this thesis. Accordingly, we have developed some models using ISS(2,3) mechanism and tried to study these BSM phenomena in the models. The following paragraphs provide an outline of this thesis, offering a brief overview of the contents covered in each chapter.

We begin Chapter 1 of this thesis with a brief introduction about the emergence and history of neutrinos which is followed by a discussion on its advancements in theoretical and experimental research. We then provide a short discussion on Standard Model of particle physics, focusing primarily on its drawbacks based on which we have formed the objectives of our work. Furthermore, this chapter includes a reasonable description on different BSM phenomena and symmetry groups that we have used to construct the models for the works of this thesis.

In Chapter 2 we have discussed a model that has been built using $\Gamma(3)$ modular group in ISS(2,3) mechanism. As $\Gamma(3)$ is isomorphic to A_4, so to realize this model we have used A_4 and Z_3 symmetry groups. Apart from neutrino phenomenology, we have studied two important BSM phenomena in this model i.e. neutrinoless double beta decay (NDBD) and lepton flavor violation (LFV). We have evaluated effective Majorana mass of electron neutrino for NDBD and calculated the branching ratio of cLFV process $\mu \to e\gamma$ for this model. Further, we have also checked for possible deviations from unitarity conditions for the mixing matrix.

In Chapter 3 we have presented the results and findings from our study of matter-antimatter asymmetry and dark matter. For this purpose we have extended minimal inverse seesaw with a Higgs-like scalar triplet $\eta = (\eta_1, \eta_2, \eta_3)$. The neutral components of η after symmetry breaking will serve as the probable dark matter candidate for our work. We have tried to explore BAU through resonant leptogenesis by observing the decay of light quasi-Dirac pairs. We have also evaluated the neutrino parameters for this model. The outcomes from our analysis show that the model is consistent with the results obtained from different cosmological observations and ongoing experiments.

In Chapter 4 we have constructed a model by using the non-abelian discrete flavor symmetry group A_4. Here we have examined the effects of texture zeros in this model that has been built in ISS(2,3). Along with the scalar triplet η, there are five flavons present in this work. Our aim is to understand the origin of texture zero structures of neutrino mass matrix by implementing 2-0 conditions on Dirac mass matrix (M_D) of neutrinos. In addition to this, we have also studied the phenomena of dark matter in this model.

The final chapter of this thesis i.e. Chapter 5 includes an overview of our entire work. It summarises the key observations of all the chapters and highlights some of the possible future prospects of this thesis.