Abstract

The Standard Model (SM) of particle physics achieved remarkable success in modern physics when the Higgs boson was discovered in 2012, solidifying its status as one of the most successful theories. It gave us a remarkable insight into the fundamental nature of the universe. However, the SM has many shortcomings and is far from providing a complete picture. For instance, the SM encounters a challenge in understanding the properties of neutrinos.

Contrary to the prediction from the SM, evidence from various neutrino oscillation experiments suggests that neutrinos possess non-zero masses and their flavours mix. This is concrete experimental proof of Beyond the Standard Model (BSM) physics. BSM frameworks usually include the extension of the SM particle content, scalars, and/or fermions. The seesaw mechanism is one such framework that explains the smallness of neutrino mass. The seesaw mechanism can explain the origin of neutrino masses and the matter-antimatter asymmetry of the universe. In the simplest seesaw framework (type-I seesaw mechanism), the heavy right-handed neutrinos introduced can potentially decay out of equilibrium in the early universe. The decay of these particles can cause a lepton asymmetry, which eventually gets transformed into a baryon asymmetry by processes involving the violation of baryon (B) and lepton (L) numbers, known as sphaleron processes. However, in standard thermal leptogenesis with hierarchical masses of the right-handed neutrinos, the observed value of BAU can be explained if their mass scale is $\mathcal{O}(10^9)$.

Neutrino oscillation suggests neutrinos transition between different flavour states as they travel through space. Theoretically, the neutrino flavour mixing

can be described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. According to this matrix, the three flavour eigenstates of neutrinos are mixtures of the three mass eigenstates. As neutrinos propagate through space, these mass eigenstates evolve at different rates, leading to oscillations between different flavours. According to various neutrino oscillation experiments, neutrino mixing has an intricate structure. The theoretical origin of such a mixing pattern is of great interest in the realm of particle physics. One of the popular ways of explaining the observed mixing pattern is by augmenting the SM gauge symmetry with a non-Abelian discrete symmetry like S_3, S_4, A_4, A_5, etc. This approach was first inspired by noticing that the elements of the PMNS matrix bore a resemblance to Clebsch-Gordon coefficients associated with non-Abelian discrete groups. Furthermore, if these distinct groups exhibit three-dimensional irreducible representations, the amalgamation of SM leptonic doublets into a single representation of the group becomes feasible, which would account for the three neutrino generations.

Experimental searches in neutrino physics have yielded invaluable insights into neutrino oscillation phenomena. The evolution of neutrino flavours during propagation has been probed through experiments such as Super-Kamiokande, SNO, KamLAND, and more recently, the NOνA and T2K experiments. These experiments have significantly enhanced our understanding of neutrino oscillation parameters, shedding light on mixing angles, mass-squared differences, and the emergence of leptonic CP violation. The current data exhibits a marginal statistical inclination toward maximal CP violation. However, the value of Dirac CP phases is not as established as the mixing angles according to various neutrino oscillation experiments.

Motivated by the factors mentioned above, in this thesis, we have built several models and thoroughly examined their feasibility.

Chapter 1: The introductory chapter of this thesis provides a comprehensive overview of neutrinos, starting with a brief historical description. We examine the inherent limitations of the Standard Model of particle physics in explaining the neutrino properties, particularly addressing the challenges it encounters. The chapter includes a detailed description of neutrino oscillations and summarizes the current status of observables related to neutrino oscillation phenomena. Moreover, it delves into the motivations driving the exploration of frameworks beyond the Standard Model, while briefly outlining the mechanisms of neutrino mass generation. A detailed discussion of the baryon asymmetry of the universe (BAU) constitutes a crucial component of this chapter.

Chapter 2: This chapter discusses a simple model based on the S_4 flavour symmetry group within the framework of the minimal seesaw model. Within this framework, we showcase the S_4 flavour symmetric realization of trimaximal (TM_1) mixing patterns of neutrinos. The model's description requires six real parameters, and we undertake a comprehensive analysis by using the global fit of experimental data on neutrino oscillations. Additionally, our investigation extends to exploring the Majorana nature of neutrinos, particularly through the examination of neutrinoless double beta decay phenomena. Furthermore, we explore the model's potential in explaining the mechanism of baryogenesis via resonant leptogenesis, investigating its viability within this theoretical construct. From the results obtained in this chapter, we conclude that the model disfavours the normal hierarchy of neutrino masses.

Chapter 3: This chapter demonstrates the use S4 flavour symmetry in explaining the theoretical origin of neutrino mixing. Using the minimal form of the inverse seesaw framework, we discuss a S_4 flavour symmetric model that can fit the neutrino oscillation data. This model extends the particle content of the Standard Model by incorporating two additional RH and two gauge singlet neutrinos. Within this context, we introduce an augmentation of the Standard Model gauge symmetry with $S_4 \times Z_3 \times Z_4$ symmetry. Our analysis evaluates the model's capability to explain the experimental neutrino oscillation data through a systematic chi-squared analysis. Additionally, we investigate the phenomenon of neutrinoless double beta decay within the constructed model.

Chapter 4: This chapter focuses on the investigation of resonant leptogenesis within the framework of a minimal radiative seesaw model. Specifically, it focuses on the examination of the minimal scotogenic model, characterized by an extension of the Standard Model gauge symmetry through the inclusion of a Z_2 symmetry. The study concentrates on a scenario where two nearly degenerate right-handed neutrinos facilitate resonant leptogenesis, a phenomenon manifesting at lower temperatures. The CP-violating phases in the neutrino mixing matrix serve as a source of CP violation required for a successful leptogenesis-based explanation of the observable BAU. Furthermore, the parameter space, including the low-energy CP-violating phases constrained by the requirements of successful baryogenesis, is employed to analyze the phenomenon of neutrinoless double beta decay.

Chapter 5: In our final investigation, we study the scenario of resonant leptogenesis in the minimal inverse seesaw (ISS) model, specifically focusing on the ISS(2, 2) variant. This model, an extension of the Standard Model, introduces two additional RH neutrinos alongside two SM gauge singlet neutrinos. Our investigation centers on thoroughly examining the parameter space inherent to the ISS(2, 2) model, particularly to determine the conditions conducive to successful leptogenesis. We are exploring the possibility of creating the observed baryon asymmetry in the universe through leptogenesis. We focus on scenarios where low-energy CP phases are the only source of CP violation. Furthermore, for effective resonant leptogenesis, we are examining the effects of a texture-zero configuration in the Dirac mass matrix on the model's parameter space.

Chapter 6: In this concluding chapter, we summarize the key findings derived from our research and outline the potential directions for future exploration and advancement in this field of study.