Abstract

The Standard Model (SM) of particle physics is one of the most successful theories in modern science. It explains the behavior of the fundamental particles that make up the universe and describes how they interact through three of the four fundamental forces: the electromagnetic, weak, and strong forces. The SM includes particles like quarks, which form protons and neutrons, and leptons, such as electrons and neutrinos. One of the major achievements of the Standard Model was the prediction of the Higgs boson, a particle responsible for giving mass to other particles. This prediction was confirmed in 2012 when the Higgs boson was discovered at the Large Hadron Collider (LHC), a significant success for the model.

Beyond the Standard Model refers to theories and ideas that aim to address the gaps and limitations of the Standard Model (SM) of particle physics. While the Standard Model has been very successful in explaining many aspects of the universe, such as the behavior of fundamental particles and three of the four fundamental forces, it does not provide a complete picture.

One major limitation is that the SM does not include gravity, which is described by the theory of General Relativity. Additionally, the SM cannot explain dark matter and dark energy, which make up most of the universe. It also struggles to explain why neutrinos have mass, as the original SM considered them massless. The matter-antimatter asymmetry observed in the universe, where there is more matter than antimatter, is another issue not fully explained by the SM. To address these gaps, physicists have proposed several theories beyond the Standard Model. These include Supersymmetry (SUSY), which suggests the existence of new particles, and String Theory, which attempts to unify all fundamental forces, including

gravity. Other ideas involve explaining neutrino mass through mechanisms like the seesaw model or introducing new particles like sterile neutrinos.

Neutrino oscillations are a phenomenon where a neutrino changes its flavor as it travels. Neutrinos come in three different flavors: electron neutrinos, muon neutrinos, and tau neutrinos. Initially, scientists believed that neutrinos were massless and did not change flavor. However, experiments have shown that neutrinos can switch between these flavors, a process known as oscillation. For neutrino oscillations to happen, neutrinos must have mass, though their mass is very small compared to other particles. This discovery was significant because the original Standard Model of particle physics did not account for neutrino mass. The detection of neutrino oscillations provided clear evidence that the Standard Model is incomplete. Neutrino oscillations are important because they help explain some of the mysteries in physics, such as why the number of electron neutrinos detected from the Sun is less than expected.

In the context of particle physics, the non-Abelian discrete symmetries like A_4, S_4, $\Delta(54)$ etc, are used to explain the behavior of particles and their interactions, especially in theories beyond the Standard Model. These symmetries can help organize particles into groups and predict how they transform under certain conditions. Non-Abelian discrete symmetries have been applied in areas like neutrino physics to explain phenomena such as neutrino oscillations or mass patterns. Researchers use these symmetries to develop models that extend the Standard Model and help explain some of the unanswered questions in physics, such as the nature of dark matter or the origin of particle masses.

Experiments in neutrino physics such as Super-Kamiokande, Sudbury Neutrino Observatory, Daya Bay, NOνA and DUNE aim to study the properties and behavior of neutrinos. These experiments have provided crucial insights, such as the discovery that neutrinos have mass and can change their flavors through a process known as neutrino oscillation.

Motivated by the factors discussed above, this thesis presents several models that we have developed and carefully analyzed for their viability.

Chapter 1: This thesis begins with an introductory chapter that provides an in-depth examination of neutrinos, tracing their historical development. This chapter highlights the limitations of the Standard Model of particle physics in understanding neutrino properties and behavior. It explores neutrino oscillations, reviews the latest research on related phenomena, and discusses the rationale for exploring theories beyond the Standard Model, including mechanisms for neutrino mass generation.

Chapter 2: This chapter gives a detailed discussion of the Baryon Asymmetry of the Universe which refers to the observed imbalance between matter and antimatter in the universe. This chapter also introduces Dark Matter which is a form of matter that does not emit, absorb, or reflect light, making it invisible and detectable only through its gravitational effects. The interplay between baryon asymmetry and dark matter is an active area of research, as understanding both could shed light on the fundamental structure and evolution of the universe.

Chapter 3: This chapter analysis involves enhancing the $\Delta(54)$ flavor symmetry model with Inverse Seesaw mechanism along with two SM Higgs through the incorporation of distinct flavons. The exact tri-bimaximal neutrino mixing pattern undergoes a deviation as a result of the incorporation of extra flavons, leading to the emergence of a non-zero reactor angle θ_{13} that aligns with the latest experimental findings. It was found that for our model the atmospheric oscillation parameter occupies the lower octant for normal hierarchy case. We also examine the parameter space of the model for normal hierarchy to explore the Dirac CP (δ_{CP}), Jarlskog invariant parameter (J) and the Neutrinoless double-beta decay parameter ($m_{\beta\beta}$) and found it in agreement with the neutrino latest data.

Chapter 4: This chapter involves augmenting the $\Delta(54)$ flavor symmetry model by incorporating two Standard Model Higgs particles into the Double ISS mechanism. The mass matrices are discussed numerically in the framework of $\Delta(54)$ flavor for Majorana neutrinos. We introduced Vector like fermions and Weyl fermions, which are gauge singlets in the Standard Model and produces Majorana mass terms. The mass matrices deviate from the tribimaximal neutrino mixing pattern, resulting in the production of a non-zero reactor angle θ_{13}. We found that the atmospheric oscillation parameter (θ_{23}) occupies the upper octant under the normal hierarchy situation. We also study the CP violation (δ_{CP}) , Jarlskog invariant parameter (J), and Neutrinoless double-beta decay parameter (m_{ee}) in the parameter space of the normal hierarchy model.

Chapter 5: This chapter investigates the possibility of baryogenesis in the proposed framework via resonant leptogenesis. We have the non-zero value for resonantly enhanced CP asymmetry originating from the decay of right-handed neutrinos at the TeV scale, accounting for flavor effects. The evolution of lepton asymmetry is systematically analyzed by numerically solving a set of Boltzmann equations, leading to the determination of the baryon asymmetry with a magnitude of $|\eta_B| \approx 6 \times 10^{-10}$. This outcome is achieved by selecting specific values for the right-handed neutrino mass $M_1 = 10$ TeV and mass splitting, $d \approx 10^{-8}$.

Chapter 6: In this chapter we discuss the neutrino phenomenology in a $\Delta(54)$ discrete flavor symmetry and evaluate the relic abundance of dark matter (DM) and active neutrino-DM mixing angle considering various cosmological constraints. We introduced two Standard Model Higgs particles along with vector-like fermions and a new particle (S) which is a gauge singlet in the Standard Model. This modification leads to a mass matrix that diverges from the tribimaximal neutrino mixing pattern resulting in a non-zero reactor angle (θ_{13}). We also incorporated a $Z_2 \otimes Z_3 \otimes Z_4$ symmetry for the specific interactions in our model. The additional particle S is a sterile neutrino which is considered to be a probable dark matter candidate with mass in keV range.

Chapter 7: In this concluding chapter, we summarize the main findings from our research and highlight potential avenues for future exploration and development in this field of study.