Chapter 1

Introduction

1.1 What are Neutrinos

Neutrinos are elementary particles that belong to the lepton family. They are fundamental particles and are not composed of smaller components. Neutrinos have a tiny, but non-zero mass. Their exact mass is not well known but is significantly smaller than that of other subatomic particles like protons or electrons. They have no electric charge, making them immune to electromagnetic forces. This makes them very difficult to detect, as they do not interact with charged particles or electromagnetic fields.

Neutrinos interact only via the weak nuclear force (one of the four fundamental forces of nature) and gravity. The weak interaction is so subtle that trillions of neutrinos pass through the Earth every second without causing any detectable impact. There are three known flavors of neutrinos. They are electron neutrinos, muon neutrinos and tau neutrinos which correspond to their association with their respective charged lepton counterparts.

One of the most intriguing aspects of neutrinos is their ability to change from one flavor to another as they travel, a phenomenon known as Neutrino Oscillation. This discovery confirmed that neutrinos have mass, which was a significant finding in particle physics.

1.1.1 Where Do Neutrinos Come From

Neutrino production arises from a range of natural processes, including nuclear reactions. Neutrinos are emitted during nuclear fusion reactions, like those that power the Sun and other stars. The Sun produces huge numbers of neutrinos through nuclear reactions. These neutrinos are called solar neutrinos and travel all the way to Earth. Certain types of radioactive decay, particularly beta decay, produce neutrinos. These processes occur in both natural and man-made environments. Supernovae, exploding stars, release a vast number of neutrinos. Some high-energy neutrinos also come from mysterious cosmic sources, such as black holes or active galactic nuclei.

Neutrinos are constantly being produced in Earth's atmosphere. This happens when high energy cosmic rays particles from space collide with atoms in the upper atmosphere. These collisions create showers of particles including neutrinos. These atmospheric neutrinos are mostly muon neutrinos and electron neutrinos. Despite being produced in large numbers, neutrinos are incredibly difficult to detect because they rarely interact with matter. They pass through the atmosphere, the Earth, and even us without being stopped or noticed. Special detectors located deep underground, such as the Super-Kamiokande in Japan [1], and IceCube in Antarctica [2], are designed to capture rare neutrino interactions and study them.

Nuclear reactors are significant sources of neutrinos which are produced during the process of nuclear fission. In a reactor atoms like uranium or plutonium split into smaller atoms releasing energy along with antineutrinos as byproducts.

1.1.2 Discovery of Neutrinos

Neutrinos are tiny, almost invisible particles that move very fast, close to the speed of light. In 1930, Austrian physicist Wolfgang Pauli proposed the idea of a new particle called the neutrino to solve a problem in physics [3]. At the time, scientists noticed that in a process called beta decay (a type of radioactive decay), some energy seemed to disappear, which went against the law of conservation of energy. Pauli suggested that this missing energy was carried away by a very small, neutral particle that could not be easily detected. He called it the neutrino. Pauli's idea was eventually proven correct when neutrinos were detected in 1956. This proposal helped explain beta decay and showed that energy is conserved in all processes.

In 1956, physicists Clyde Cowan and Frederick Reines successfully detected the electron neutrino (ν_e), a tiny and elusive particle that had been proposed by Wolfgang Pauli in 1930. They conducted their experiment near a nuclear reactor, which produced a large number of neutrinos during nuclear reactions. Using special detectors, Cowan and Reines were able to observe the interaction of neutrinos with matter, confirming their existence. This discovery was a major breakthrough in particle physics, as it provided the first direct evidence of neutrinos and helped to explain the process of beta decay. For their work, Reines later received the Nobel Prize in Physics in 1995.

In 1962, physicists Leon Lederman, Melvin Schwartz, and Jack Steinberger made a groundbreaking discovery by identifying a second type of neutrino, the muon neutrino(ν_μ). This was important because, until then, only the electron neutrino had been observed. Using a particle accelerator at Brookhaven National Laboratory, they produced beams of neutrinos and found that some neutrinos were associated with muons rather than electrons. This discovery proved that there were different flavors of neutrinos. For their pioneering work, all three scientists were awarded the Nobel Prize in Physics in 1988.

In the year 2000, the DONUT (Direct Observation of the Nu Tau) collaboration made a historic discovery by identifying the tau neutrino (ν_τ). They are the third type of neutrino. The experiment took place at Fermilab in the United States, where scientists used a particle accelerator to create high-energy collisions that produced tau neutrinos. These particles were extremely difficult to detect because of their weak interactions with matter. The discovery of the tau neutrino completed the neutrino family and was a crucial step in understanding the Standard Model of particle physics.

1.1.3 Known and Unknown of Neutrinos

One of the most significant discoveries in neutrino physics is the phenomenon of neutrino oscillation, where a neutrino changes its flavor as it propagates through space. This implies that neutrinos have mass and that the flavor states are superpositions of mass eigenstates. The key parameters in neutrino oscillations include:

1. Mixing Angles: The three mixing angles of neutrinos, θ_{12}, θ_{23} and θ_{13}, are part of the PMNS matrix which describes neutrino oscillations. These angles are determined experimentally through studies of neutrino oscillations in solar, atmospheric, reactor and accelerator experiments.

2. Mass-Squared Differences: The mass-squared differences of neutrinos, Δm^2_{12} and Δm^2_{23}, are fundamental parameters in neutrino physics. They are critical in understanding neutrino oscillations, as the oscillation probability depends on the differences in the squares of the neutrino masses rather than their absolute values.

3. CP Violation Phase: A complex phase δ_{CP} that could explain the matter-antimatter asymmetry in the universe. It refers to the phenomenon where the behavior of neutrinos differs from that of their antiparticles under the combined operations of charge conjugation and parity transformation.

NuFit 6.0 is the latest global fit of neutrino oscillation parameters. NuFit is an important resource for the global neutrino physics community, providing the best-fit values and confidence intervals for the parameters governing neutrino oscillations. These parameters are essential for understanding how neutrinos change their flavors as they propagate through space and matter, as well as their mass-squared differences and mixing angles. The NuFit framework provides a state of the art global analysis of neutrino oscillation parameters, furnishing the neutrino physics community with critical insights into the fundamental parameters governing neutrino oscillations. One may refer to “NuFIT 6.0: Three-neutrino fit based on data available in September 2024” by Esteban, Ivan, et al [4].

Parameter	Normal Ordering (NO)	Inverted Ordering (IO)
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.308^{+0.012}_{-0.011}$
$\sin^2\theta_{23}$	$0.561^{+0.018}_{-0.023}$	$0.562^{+0.016}_{-0.021}$
$\sin^2\theta_{13}$	$0.02195^{+0.00056}_{-0.00058}$	$0.02224^{+0.00059}_{-0.00057}$
Δm^2_{21} $(10^{-5}$ eV$^2)$	$7.49^{+0.21}_{-0.20}$	$7.49^{+0.21}_{-0.20}$
Δm^2_{3l} $(10^{-3}$ eV$^2)$	$+2.534^{+0.027}_{-0.027}$	$-2.510^{+0.032}_{-0.024}$
$\delta_{\rm CP}$ $(^\circ)$	177^{+41}_{-25}	285^{+27}_{-32}

Table 1.1: Best-fit values of neutrino oscillation parameters from NuFit 6.0. The parameter Δm^2_{3l} refers to Δm^2_{31} for normal ordering (NO) and Δm^2_{32} for inverted ordering (IO) [4]

Despite significant advancements, numerous unknowns and open questions remain, driving ongoing research and experimentation. This note explores the key unknowns in neutrino physics, highlighting the mysteries that scientists aim to unravel to deepen our understanding of neutrinos and their role in the cosmos.

1. Absolute Neutrino Mass Scale: While neutrino oscillation experiments have confirmed that neutrinos possess mass and provided measurements of the differences in the squares of their masses, the absolute masses of the three neutrino flavors remain undetermined.

2. Neutrino Mass Hierarchy: The mass hierarchy refers to the ordering of the neutrino mass states. There are two possible scenarios, Normal Ordering(NO), $m_1 < m_2 < m_3$ and Inverted Ordering (IO), $m_3 < m_1 < m_2$.

3. Nature of Neutrinos: Neutrinos could be either Dirac particles (distinct from their antiparticles) or Majorana particles (identical to their antiparticles). Determining their nature has profound implications for mass generation mechanisms. Majorana masses can arise from different theoretical frameworks compared to Dirac masses.

4. Sterile Neutrinos: The Standard Model includes three active neutrino flavors. However, several experimental anomalies suggest the possible existence of sterile neutrinos, which do not interact via the Standard Model forces except gravity. Sterile neutrinos could explain anomalies such as those observed in LSND, MiniBooNE, and reactor neutrino experiments. They can also provide dark matter candidates, if they possess the right properties.

1.1.4 Neutrino Oscillation

Neutrino oscillation is a quantum mechanical phenomenon where a neutrino created with a specific lepton flavor (electron, muon, or tau) can transform into another flavor as it propagates through space. This behavior implies that neutrinos have mass and that the flavor states are quantum superpositions of mass eigenstates. The Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix mathematically relates the flavor eigenstates to the mass eigenstates [5]. It is a 3×3 unitary matrix defined as:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_{PMNS} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \tag{1.1}$$

In other words:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle \quad \text{for} \quad \alpha = e, \mu, \tau \tag{1.2}$$

Here, $U_{\alpha i}$ are the elements of the PMNS matrix, representing the amplitude for a neutrino of flavor α to be in mass eigenstate i. The PMNS matrix can be parametrized in terms of three mixing angles and one CP-violating phase in the standard parametrization. The general form is:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} .M \tag{1.3}$$

Multiplying these matrices together, the standard parametrization of the PMNS matrix becomes:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}c_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} \tag{1.4}$$

Here, $c_{ij} = cos\theta_{ij}$, $s_{ij} = sin\theta_{ij}$ and δ_{CP} is the CP-violating phase. The matrix M has a value of det $M = 1$ for the Dirac neutrinos and $M = diag(1, e^{i\alpha_2}, e^{i\alpha_3})$ for Majorana neutrinos. If neutrinos are Majorana particles, two additional phases can be included, but these do not affect neutrino oscillations and are often omitted in oscillation studies. The mass splitting terms can be expressed as:

$$\Delta m^2_{21} = m^2_2 - m^2_1, \quad \Delta m^2_{3n} = m^2_3 - \frac{(m^2_2 + m^2_1)}{2} \tag{1.5}$$

such that, $\Delta m^2_{21} > 0$ and $\Delta m^2_{3n} \equiv \Delta m^2_{31} > 0$ is positive for Normal Mass Ordering (NO) and $\Delta m^2_{3n} \equiv \Delta m^2_{32} < 0$ is negative for Inverted Mass Ordering (IO) for the neutrino mass spectrum. The probability that a neutrino of flavor α where ($\alpha = e, \mu, \tau$) oscillates into a flavor β as it propagates is governed by several fundamental parameters within the PMNS matrix. Specifically, this probability depends on three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), CP-violating phase ($\delta_{CP}$), two mass-squared splittings ($\Delta m^2_{21}, \Delta m^2_{31}$), its energy E_ν, propagation distance L, and the density of matter passed through by the neutrino ρ, given by

$$P_{(\nu_\alpha \to \nu_\beta)} = f(\theta_{12}, \theta_{12}, \theta_{12}, \delta_{CP}; \Delta m^2_{21}, \Delta m^2_{31}; E\nu, L, \rho). \tag{1.6}$$

1.2 Neutrinos in the Standard Model

Neutrinos are fundamental particles classified as leptons within the Standard Model (SM) of particle physics. They come in three distinct flavors, electron neutrino (ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ), each associated with their corresponding charged leptons, electron (e^-), muon (μ^-) and tau (τ^-). Neutrinos are electrically neutral ($0e$), which contributes to their weakly interacting nature. They possess a spin $\frac{1}{2}$, making them fermions that follow the Pauli exclusion principle. In the original SM formulation, neutrinos were considered massless. However, experimental evidence from neutrino oscillation experiments has demonstrated that they have tiny but non-zero masses, indicating physics beyond the Standard Model.

Category	**Name**	**Symbol**	**Electric Charge**
Quarks	Up	u	$+\frac{2}{3}e$
	Down	d	$-\frac{1}{3}e$
	Charm	c	$+\frac{2}{3}e$
	Strange	s	$-\frac{1}{3}e$
	Top	t	$+\frac{2}{3}e$
	Bottom	b	$-\frac{1}{3}e$
Leptons	Electron	e^-	$-1e$
	Electron Neutrino	ν_e	$0e$
	Muon	μ^-	$-1e$
	Muon Neutrino	ν_μ	$0e$
	Tau	τ^-	$-1e$
	Tau Neutrino	ν_τ	$0e$
Bosons	Photon	γ	$0e$
	W^+ Boson	W^+	$+1e$
	W^- Boson	W^-	$-1e$
	Z Boson	Z^0	$0e$
	Gluon	g	$0e$
	Higgs Boson	H	$0e$

Table 1.2: Standard Model of Particle Physics

The Standard Model recognizes six flavors of quarks. They are Up (u), Down (d), Charm (c) , Strange (s), Top (t) and Bottom (b). These flavors are grouped into three generations. Neutrinos interact primarily through the weak nuclear force, mediated by W^+, W^- and Z bosons. These interactions are rare due to their neutral charge and small mass, making neutrinos extremely difficult to detect. They participate in both charged current interactions and neutral current interactions.

Despite its remarkable successes in describing fundamental particles and their interactions, the SM is not a complete theory. It leaves several questions unanswered, particularly regarding gravity, dark matter, and the fundamental nature of the universe. The pursuit of a more comprehensive theory, which may extend the Standard Model, continues to be one of the most exciting and challenging areas of modern physics. The evidence for non-zero neutrino masses and flavor mixing [6–9] marks a significant milestone in particle physics and serves as a compelling experimental proof of phenomena that extend beyond the Standard Model.

1.2.1 The Gauge Theory and Interactions

Gauge symmetry is a fundamental principle in the Standard Model of particle physics. The theory describs how the forces between particles are mediated by gauge bosons, based on symmetry principles. It is rooted in the concept that the laws of physics should remain unchanged under certain transformations, leading to interactions via force carriers. The Standard Model relies on three main gauge symmetries, which are $SU(3)$ (for the strong interaction), $SU(2)$ (for the weak interaction) and $U(1)$ (for the electromagnetic interaction). These symmetries correspond to the three fundamental forces described by the Standard Model: the strong, weak, and electromagnetic forces. Quantum Chromodynamics (QCD) governs the strong force, described by the $SU(3)$ symmetry. This force acts on particles with color charge (quarks) and is mediated by gluons. Electroweak Theory unifies the weak and electromagnetic forces under the $SU(2) \times U(1)$ symmetry. The weak force, responsible for particle decays and flavor changes, is mediated by W and Z bosons, while the electromagnetic force is mediated by the photon. Gauge symmetry ensures that these interactions arise naturally from requiring the physics to remain invariant under local transformations of these symmetry groups. The exchange of gauge bosons maintains this invariance, leading to the fundamental interactions that govern particle behavior.

1.2.2 Spontaneous Symmetry Breaking and the Higgs Mechanism

Spontaneous symmetry breaking is a key concept in the Standard Model that explains how particles acquire mass without violating gauge symmetry. It occurs when the underlying laws of a system are symmetric, but the system itself settles into an asymmetric state. This breaking is crucial for differentiating between the electromagnetic and weak forces in the electroweak theory.

The Higgs mechanism provides a framework for this process. It introduces the Higgs field, which permeates all of space. When the universe cooled after the Big Bang, the Higgs field acquired a non-zero value everywhere, breaking the $SU(2) \times U(1)$ electroweak symmetry. This spontaneous breaking gave mass to the W and Z bosons (mediators of the weak force) while leaving the photon massless, preserving electromagnetic symmetry.

The Higgs boson is the quantum manifestation of fluctuations in this field, and its discovery in 2012 at CERN's Large Hadron Collider confirmed the Higgs mechanism. This process explains how elementary particles, like the W and Z bosons, and even fermions, gain mass by interacting with the Higgs field.

1.3 Neutrinos Beyond the Standard Model

The Standard Model of particle physics is a highly successful theory that describes the fundamental particles and their interactions, excluding gravity. It has accurately predicted a wide range of phenomena and was confirmed by the discovery of the Higgs boson in 2012. However, despite its successes, the Standard Model is known to be incomplete. Beyond the Standard Model (BSM) refers to a collection of theoretical frameworks and ideas that aim to address the limitations of the SM and answer questions it cannot currently explain.

1.3.1 Motivations for BSM

The Dark Matter and Dark Energy is one of the motivation for BSM. Observations indicate that about 27% of the universe is composed of dark matter and 68% dark energy, neither of which is accounted for in the Standard Model. Another motivation is the non-zero neutrino masses. The SM originally posited neutrinos as massless particles. However, experiments have confirmed that neutrinos have a small but nonzero mass, necessitating extensions to the SM.

Another reason for BSM is the Hierarchy Problem. The SM does not explain why the Higgs boson mass is much lighter than the Planck scale, leading to questions about the naturalness of the Higgs mass. Again the observable universe is dominated by matter over antimatter, a phenomenon not fully explained by the SM. The SM successfully unifies the electromagnetic, weak, and strong forces but does not incorporate gravity, suggesting the need for a more comprehensive theory. Incorporating gravity into the quantum framework of the SM remains unresolved, pointing towards the necessity of new physics.

1.3.2 BSM Theories

Several theoretical frameworks have been proposed to extend the Standard Model:

1. Supersymmetry (SUSY): Proposes a symmetry between fermions and bosons, predicting a superpartner for each SM particle. Addresses the hierarchy problem, provides candidates for dark matter, and facilitates gauge coupling unification. Despite extensive searches, no supersymmetric particles have been confirmed experimentally as of the latest data.

2. Grand Unified Theories (GUTs): Aim to unify the electromagnetic, weak, and strong forces into a single force at high energy scales. Some examples of

GUTs are SU(5) and SO(10) models. Predict phenomena like proton decay, which is being searched for in experiments.

3. Extra Dimensions: Suggests the existence of additional spatial dimensions beyond the familiar three. Some models of are Kaluza-Klein theory, Large Extra Dimensions (ADD model), Randall-Sundrum models. This symmetry explains the weakness of gravity and offer solutions to the hierarchy problem.

4. String Theory: Proposes that fundamental particles are one-dimensional strings rather than point-like particles. It incorporates gravity and aims for a unified description of all forces and particles. This theory lacks direct experimental evidence and has a vast landscape of possible solutions.

5. Neutrino Mass Models: Seesaw mechanisms, including Type I, Type II, Type III, and Inverse Seesaw, facilitate the generation of naturally small neutrino masses through the introduction of heavy mediators, such as, Right-handed neutrinos, Scalar triplets, Fermion triplets and Sterile neutrinos. These seesaw mechanisms effectively suppress neutrino masses while accommodating the observed neutrino mass splittings and mixings, providing a well-motivated solution to the neutrino mass problem.

1.4 Neutrino Experiments

1.4.1 Solar Neutrino Experiments

Solar neutrino experiments are important in understanding both the processes powering our Sun and the fundamental properties of neutrinos. Solar neutrinos are produced in vast quantities through nuclear reactions in the Sun's core which provides a unique window into both stellar physics and particle physics. Studying these neutrinos has led to groundbreaking discoveries, including the resolution of the solar neutrino problem and the confirmation of neutrino oscillations, which imply that neutrinos have mass.

Homestake Experiment

Initiated by Raymond Davis Jr. in the late 1960s at the Homestake Gold Mine in South Dakota, USA, this pioneering experiment was the first to attempt the direct detection of solar neutrinos [10]. This method utilizes a large tank filled with perchloroethylene which is a cleaning fluid rich in chlorine-37. Solar electron neutrinos interact with chlorine-37 nuclei via the inverse beta decay reaction:

$$\nu_e +^{37} Cl \rightarrow e^- +^{37} Ar \tag{1.7}$$

The produced argon-37 atoms were extracted and counted.

GALLEX and GNO Experiments

GALLEX was conducted in the Gran Sasso Laboratory in Italy during the 1990s. This experiment use gallium-71 to detect lower-energy solar neutrinos, particularly those from the proton-proton (pp) chain [11]:

$$\nu_e +^{71} Ga \rightarrow e^- +^{71} Ge \tag{1.8}$$

GNO (Gallium Neutrino Observatory) is an extension of GALLEX. It aimed to increase the sensitivity and reduce systematic uncertainties [12].

Sudbury Neutrino Observatory(SNO)

The Sudbury Neutrino Observatory was a groundbreaking neutrino experiment located in the Creighton Mine near Sudbury, Ontario, Canada. Operational from 1999 to 2006, SNO played a pivotal role in resolving the long-standing solar neutrino problem and provided compelling evidence for neutrino oscillations, thereby confirming that neutrinos have mass. By utilizing heavy water (D_2O) as its detection medium, SNO was uniquely equipped to detect all three flavors of neutrinos, distinguishing between electron neutrinos produced in the Sun and the other flavors generated through oscillations [13]. The detection method uses charge-current interaction

$$\nu_e + d \rightarrow p + p + e^- \tag{1.9}$$

The detection of the emitted electron via Cherenkov radiation allows measurement of the electron neutrino flux.

1.4.2 Atmospheric Neutrino Experiments

Atmospheric neutrino experiments complement accelerator-based studies by providing a diverse set of neutrino energies and baselines. They are instrumental in investigating parameters such as the neutrino mass hierarchy, mixing angles, and potential CP violation in the lepton sector.

MINOS (Main Injector Neutrino Oscillation Search)

MINOS was located at Fermilab in the United States. It utilizes the NuMI (Neutrinos at the Main Injector) beamline [14]. It comprised two detectors, the Near Detector at Fermilab and the Far Detector situated 735 kilometers away in the Soudan Mine in Minnesota. MINOS was designed to precisely measure neutrino oscillation parameters, specifically the mixing angle θ_{23} and the mass-squared difference Δm^2_{32}, by comparing the neutrino flux and energy spectrum between the Near and Far Detectors. In addition to its accelerator-based measurements, MINOS had sensitivity to atmospheric neutrinos that interacted within the Far Detector. By analyzing upward-going neutrinos that traversed the Earth, MINOS contributed to confirming neutrino oscillations and provided complementary data to its beam-based studies.

T2K (Tokai to Kamioka)

T2K is a long-baseline neutrino experiment in Japan, sending a beam of muon neutrinos from the Japan Proton Accelerator Research Complex (J-PARC) in Tokai to the Super-Kamiokande detector in Kamioka, 295 kilometers away [15]. T2K aims to study neutrino oscillations, particularly the appearance of electron neutrinos in a muon neutrino beam, which is crucial for investigating CP violation in the lepton sector. It focuses on measuring parameters like θ_{13} and δ_{CP}. T2K incorporates atmospheric neutrino data through its Near Detector (ND280) and the Super-Kamiokande Far Detector. This allows for cross-validation of oscillation parameters and enhances the overall sensitivity to various oscillation channels.

NOνA (NuMI Off-axis ν_e Appearance)

NOνA is a long-baseline neutrino experiment in the United States, utilizing the NuMI beamline at Fermilab. It features two detectors: a Near Detector located at Fermilab and a Far Detector situated in Ash River, Minnesota, 810 kilometers away. It focuses on studying neutrino oscillations, particularly the appearance of electron neutrinos in a muon neutrino beam. It aims to determine the neutrino mass hierarchy, measure the mixing angle θ_{23}, and search for CP violation in the neutrino sector. The far detector is capable of detecting atmospheric neutrinos, providing additional data to complement its beam-based measurements. This approach enhances the ability to probe oscillation parameters across different energy ranges and path lengths [16].

1.4.3 Reactor Neutrino Experiments

Reactor neutrino experiments have been instrumental in measuring key neutrino oscillation parameters, particularly the mixing angle θ_{13}. They also explore phenomena such as the reactor neutrino anomaly, which hints at possible new physics beyond the Standard Model, including sterile neutrinos. Additionally, reactor experiments contribute to the determination of the neutrino mass hierarchy and precision tests of the three-neutrino oscillation framework.

Daya Bay Reactor Neutrino Experiment

It is Located near the Daya Bay Nuclear Power Plant in Guangdong Province, China. This experiment comprises multiple detectors situated at varying baselines from the reactor cores. The experimental setup includes eight antineutrino detectors grouped into near and far halls to monitor neutrino flux before and after oscillation. Daya Bay was primarily designed to measure the neutrino mixing angle

θ_{13} with high precision by observing the disappearance of $\bar{\nu}_e$ over short baselines [17].

Double Chooz

It is situated near the Chooz Nuclear Power Plant in the Ardennes region of France, Double Chooz features a near detector close to the reactors and a far detector located approximately 1 km away [18]. This experiment aims to measure θ_{13} by comparing the flux at near and far detectors, thereby minimizing systematic uncertainties related to reactor neutrino production.

RENO (Reactor Experiment for Neutrino Oscillation)

It is Located at the Hanbit Nuclear Power Plant in South Korea, RENO employs near and far detectors positioned at distances of approximately 290 meters and 1,400 meters from the reactors, respectively. Similar to Daya Bay and Double Chooz, RENO's main goal is to measure θ_{13} by detecting the disappearance of $\bar{\nu}_e$ over the specified baselines [19].

1.5 Inverse Seesaw Mechanism

The Inverse seesaw model provides a framework for generating neutrino masses, featuring mediator masses near the electroweak scale. This mechanism is distinguished by a tiny mass parameter (μ) that governs the hierarchy of energy scales

$$\mu << v << \Lambda \tag{1.10}$$

By introducing the μ-parameter, neutrino masses are suppressed as $m_\nu \propto \mu$, allowing for large Yukawa couplings and light mediators to reproduce observed neutrino properties, thereby enhancing the phenomenological prospects compared to traditional high-energy seesaw scenarios [20].

1.5.1 Canonical Majorana inverse seesaw

The canonical Majorana inverse seesaw is a type of Inverse seesaw mechanism where the $U(1)_L$ symmetry is broken down to a residual Z_2 subgroup [20]. Under the assumption of a conserved $U(1)_L$ symmetry, one can write the Lagrangian terms as

$$\mathcal{L}_{Maj} = Y\bar{L}\tilde{H}N^c + \lambda\bar{S}^c\chi S + M\bar{S}^c N + h.c.. \tag{1.11}$$

where, $\tilde{H} = i\sigma_2 H^*$. The particles N, S, and χ are gauge singlets under the Standard Model. The Inverse seesaw formula is given below and diagramaically represented in figure.1.1

$$m_\nu = -Y\frac{v^2\mu}{M^2} \tag{1.12}$$

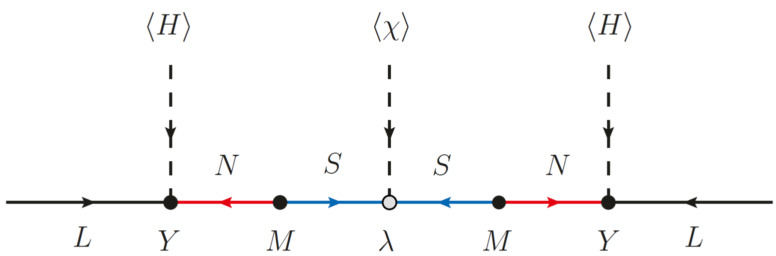

Figure 1.1: Neutrino mass generation in the standard Majorana inverse seesaw.

1.5.2 Simplest Dirac inverse seesaw

In this section, we aim to construct the inverse seesaw model for Dirac neutrinos [20]. Under the assumption of a conserved $U(1)_L$ symmetry, one can write the Lagrangian terms as

$$\mathcal{L}_{Dir} = Y\bar{L}\tilde{H}N_R + \lambda\bar{N}_L\chi\nu_R + M\bar{N}_L N_R + h.c.. \tag{1.13}$$

The Inverse seesaw formula is given below and diagramaically represented in figure.1.2

$$m_\nu = Yv\frac{\mu}{M} \tag{1.14}$$

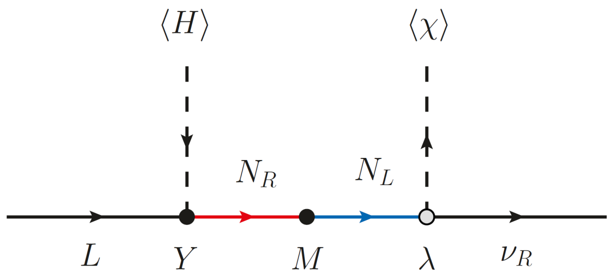

Figure 1.2: Neutrino mass generation in the Dirac inverse seesaw.

1.5.3 Majorana double inverse seesaw

To construct a double inverse seesaw model we extend the canonical inverse seesaw framework with an additional fermion S_R, possessing zero B-L charge [20]. The $SU(3)_C \times SU(2)_L \times U(1)_Y$ and $U(1)_{B-L}$ invariant Lagrangian relevant for neutrino mass generation is given by

$$\mathcal{L}_{yuk} = Y\bar{L}HN_R + M_N\bar{N}_L\bar{N}_R + M_S\bar{S}_RS_R^c + \lambda\bar{N}_L\chi\bar{S}_R + \lambda'\bar{N}_R\chi\bar{S}_R^c + h.c. \quad (1.15)$$

The Inverse seesaw formula is given below and diagramaically represented in figure.1.3

$$m_\nu = Y^2v^2\frac{\mu^2}{M_N^2M_S} \quad (1.16)$$

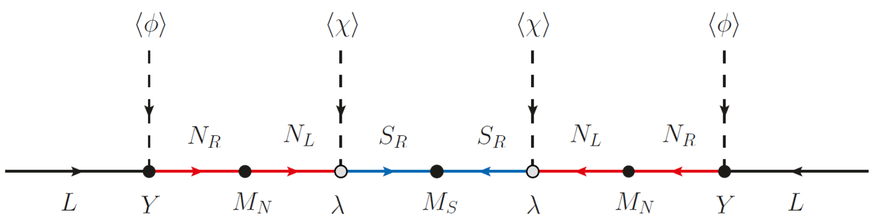

Figure 1.3: Neutrino mass generation in the Majorana double inverse seesaw.

1.5.4 Dirac double inverse seesaw

To construct a dirac double inverse seesaw model we extend the minimal dirac inverse seesaw framework with an additional VL fermions S_L, S_R, and a new singlet χ_2 [20]. The Lagrangian of the model relevant to neutrino mass generation is given by

$$\mathcal{L}_{Dir} = Y\bar{L}\tilde{H}N_R + M_N\bar{N}_L N_R + M_S\bar{S}_L S_R + \lambda_2\bar{S}_L\chi_2\nu_R + \lambda_1\bar{N}_L\chi_1\bar{S}_R + \lambda_1'\bar{S}_L\chi_1 N_R + h.c.. \tag{1.17}$$

The Inverse seesaw formula is given below and diagramaically represented in figure.1.4

$$m_\nu = -Y_N v\frac{\mu_1\mu_2}{M_N M_S} \tag{1.18}$$

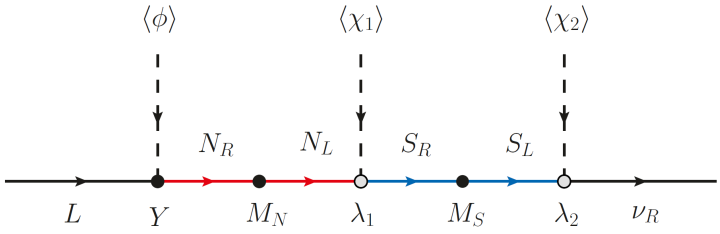

Figure 1.4: Neutrino mass generation in the Dirac double inverse seesaw.

1.6 Outline of the Thesis

Chapter 2 introduces two fundamental issues in cosmology, the baryon asymmetry of the universe (BAU) and the nature of dark matter. The chapter explains key theories and mechanisms that attempt to account for this discrepancy, such as the Sakharov conditions, which are necessary to create an asymmetry between baryons and antibaryons. The chapter also outlines the evidence for dark matter and explores candidate particles for dark matter. Together, baryon asymmetry and dark matter are presented as key unsolved problems in cosmology, shaping our understanding of the universe's composition and evolution.

Chapter 3 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 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 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 discusses 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 summarize the main findings from the research and outline potential future directions for further exploration and advancement in this field of study.

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