Phenomenological Aspects of Neutrino Masses, Mixings and Oscillations

A thesis submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

by

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DISCIPLINE OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY GANDHINAGAR

Year of submission: 2017

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Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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CERTIFICATE

It is certified that the work contained in the thesis titled **"Phenomenological Aspects of Neutrino Masses, Mixings and Oscillations"** by **Mr. Newton Nath** (Roll No. 11330024), has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

Neutrino, meaning "*the little neutral one*" (in Italian) is a sub-atomic fundamental particle. It is the most abundant particle in the universe after the photon. In 1930, Wolfgang Pauli first postulated the existence of the neutrino to explain the conservation of energy and the angular momentum in nuclear beta-decay. In the Standard Model (SM) of particle physics, there are three types of neutrinos (namely electron, muon and tau neutrino) which are electrically neutral, spin-half and massless fermions. Neutrinos cover a wide range of energies from 10^{-6} eV to 10^{18} eV which have been detected by different experiments – starting from detection of MeV neutrinos e.g, in nuclear beta-decay, solar and reactor experiments to very high energy PeV neutrinos in the IceCube experiment. In this doctoral work, we study some of the very interesting aspects of neutrino physics from both phenomenological as well as theoretical point of view.

Last few decades have witnessed remarkable developments in the field of neutrino physics coming from the observation of neutrino oscillation in terrestrial experiments. Neutrino oscillation requires that at least two of the neutrinos possesses small but non-zero mass and there is mixing between different flavors of neutrinos. Since in the SM neutrinos are massless, the phenomenon of neutrino oscillation implies physics beyond the SM. The three-flavor neutrino oscillation framework containing six oscillation parameters ($\theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, |\Delta m^2_{31}|$ and δ_{CP}) is now well established. Global analysis of neutrino oscillation data have determined some of these parameters with considerable precision. At the current juncture, the three unknown neutrino oscillation parameters are the neutrino mass hierarchy ($\Delta m^2_{31} > 0$, known as the normal hierarchy or $\Delta m^2_{31} < 0$, known as the inverted hierarchy), octant of the mixing angle θ_{23} ($\theta_{23} < 45^\circ$, known as the lower octant or $\theta_{23} > 45^\circ$, known as the higher octant) and the CP phase δ_{CP}. A major part of this doctoral work is devoted to the determination of these unresolved parameters using different oscillation experiments.

The main obstacle for an unambigous determination of these unknowns are the presence of parameter degeneracies which means different sets of oscillation parameters giving the same probability. In our study, we advocate a comprehensive way to study the remaining parameter degeneracies in the form of a generalized "*hierarchy*$-\theta_{23}-\delta_{CP}$" degeneracy. To analyze this, we consider long baseline neutrino oscillation exper-

iments NOνA and T2K and atmospheric neutrino oscillation experiment ICAL@INO. We discuss their physics reach and illustrate their synergistic effects to resolve the different degenerate solutions. We also explore the potential of the next generation superbeam experiment, DUNE to determine the different unknowns in neutrino oscillation parameters. Our study mainly focuses on the determination of the octant of θ_{23} and the CP phase δ_{CP}. In particular, we emphasize on the role played by the antineutrinos, the broadband nature of the beam and the matter effect.

Theoretically, the challange is to construct models of neutrino masses and mixing which can explain the observed values of the mass squared differences and the mixing angles. We discuss consequences of the assumption that the (Majorana) neutrino mass matrix M_ν and the charged lepton mass matrix M_l satisfy, $S_\nu^T M_\nu S_\nu = -M_\nu$, $T_l^\dagger M_l M_l^\dagger T_l = M_l M_l^\dagger$ with respect to some discrete groups S_ν, T_l contained in A_5 group. These assumptions lead to a neutrino mass spectrum with a massless neutrino and a degenerate pair of neutrinos and also constrain the mixing among them. We derive possible mixing patterns considering the various subgroups of A_5.

Another interesting question in neutrino physics is the existence of light sterile neutrinos. There are many experimental evidences which seem to support such a hypothesis. In this direction, we consider the "minimal extended type-I seesaw" (MES) model which naturally gives rise to a light sterile neutrino. We focus on the texture zero study of the various fermion mass matrices involving the charged leptons and neutrinos in this model. In this study, we obtain only two allowed one-zero textures in the neutrino mass matrix, m_ν, namely $m_{e\tau} = 0$ and $m_{\tau\tau} = 0$, having inverted hierarchical mass ordering. In the context of the MES model, we obtain extra correlations among neutrino oscillation parameters which can be tested in future oscillation experiments.

Keywords: Neutrino Physics, Neutrino Oscillation, PMNS matrix, Long-Baseline Neutrino Experiments, Atmospheric Neutrino Experiments, CP Phases, Sterile Neutrino, Texture Zero, Neutrino Mass Matrix, Flavor Antisymmetry, Type-I seesaw, MES model.

Acronyms and Abbreviations

SM	Standard Model
BSM	Beyond Standard Model
CC	Charge Current Interaction
NC	Neutral Current Interaction
LEP	Large Electron-Positron collider
VEV	Vacuum Expectation Value
PMNS	Pontecorvo Maki Nakagawa Sakata Matrix
$0\nu\beta\beta$	Neutrinoless Double Beta Decay
SSM	Standard Solar Model
DAR	Decay at Rest
DIF	Decay in Flight
UHE	Ultra High Energy
AGN	Active Galactic Nuclei
GRB	Gamma Ray Burst
GUT	Grand Unified Theories
MSW	Mikheyev Smirnov Wolfenstein Effect
PREM	Preliminary Reference Earth Model
GLoBES	General Long Baseline Experiment Simulator
NH	Normal Hierarchy
IH	Inverted Hierarchy
LO	Lower Octant
HO	Higher Octant
CPV	Charge conjugation-Parity Violation
LHP	Lower Half-Plane of δ_{CP}
UHP	Upper Half-Plane of δ_{CP}
POT	Protons on Target
LBL	Long Baseline Experiments

T2K	Tokai to Kamioka
SURF	Sanford Underground Research Facility
DUNE	Deep Underground Neutrino Experiment
NuMI	Neutrinos at the Main Injector
NOνA	NuMI Off-axis ν_e Appearance
MINOS	Main Injector Neutrino Oscillation Search
INO	India-based Neutrino Observatory
ICAL	Iron Calorimeter Detector
SK	Super-Kamiokande
SNO	Sudbury Neutrino Observatory
KATRIN	Karlsruhe Tritium Neutrino experiment
LSND	Liquid Scintillator Neutrino Detector
LArTPC	Liquid Argon Time Projection Chamber
TASD	Totally Active Scintillator Detector
ND	Near Detector
FD	Far Detector
G_F	Fermi coupling constant
SBL	Short Baseline Experiments
MES	Minimal Extended type-I Seesaw
NLO	Next-to-leading Order
ΛCDM	Λ cold dark matter

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List of Publications

Publications in Refreed Journals

1. **Newton Nath**, Monojit Ghosh, Srubabati Goswami and Shivani Gupta :
   Phenomenological study of extended seesaw model for light sterile neutrino,
   JHEP03(2017)075, arXiv: 1610.09090 [hep-ph].

2. Anjan S. Joshipura and **Newton Nath** :
   Neutrino masses and mixing in A_5 with flavour antisymmetry,
   Phys.Rev. D94, 036008 (2016), arXiv: 1606.01697[hep-ph].

3. **Newton Nath**, Monojit Ghosh, and Shivani Gupta :
   Understanding the masses and mixings of one-zero textures in 3 + 1 scenario,
   Int. J. Mod. Phys. A 31, 1650132 (2016), arXiv: 1512.00635 [hep-ph].

4. **Newton Nath**, Monojit Ghosh and Srubabati Goswami :
   The Physics of antineutrinos in DUNE and resolution of octant degeneracy,
   Nucl.Phys. B913 (2016) 381-404, arXiv : 1511.07496[hep-ph].

5. Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami, **Newton Nath** and Sushant K. Raut :
   A new look to the degeneracies in the neutrino oscillation parameters and their resolution by T2K, NOνA and ICAL,
   Phys. Rev. D 93, 013013 (2016), arXiv : 1504.06283[hep-ph].

Preprints under review

1. Srubabati Goswami and **Newton Nath** :
   Implications of the latest NOνA results,
   arXiv:1705.01274 [hep-ph].

2. K. N. Deepthi, Srubabati Goswami and **Newton Nath** :
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1. **Newton Nath**, Srubabati Goswami and K. N. Deepthi :
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2. **Newton Nath**, Monojit Ghosh and Srubabati Goswami :
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Publications Attached with Thesis

1. Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami, **Newton Nath** and Sushant K. Raut :
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