In Accompanied with the thoughts of my parents

Manju Devi and Kusheshwar Nath.

Declaration

I certify that

- The work contained in the dissertation is original and has been done by myself under the general supervision of my supervisors.
- The work has not been submitted to any other Institute for any degree or diploma.
- I have followed the guidelines provided by Tezpur University in writing the thesis.
- I have conformed to the norms and guidelines given in the Ethical Code of Conduct of the university.
- Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them by citing them in the text of the dissertation and giving their details in the references.

Ankur Nath

Department of Physics
Tezpur University
Napaam, Tezpur- 784028, Assam, India.

Dr. Ng. K. Francis
Associate Professor

Phone: 03712-275559
Fax: 03712-267005, 267006
E-Mail : francis@tezu.ernet.in

CERTIFICATE

This is to certify that the thesis entitled "**CP Violation, Mass Hierrachy and Octant Degeneracy in Terrestrial Neutrino Oscillation Experiments**" submitted to Tezpur University in the Department of Physics under the School of Sciences in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** in **Physics** is a record of original research work carried out by **Mr. Ankur Nath** under my supervision and guidance.

All helps received by him from various sources have been duly acknowledged. No part of this thesis has been submitted else where for award of any other degree.

Signature of Supervisor
(Ng. K. Francis)
Associate Professor
Department of Physics
Tezpur University
Assam, India-784028

Certificate

This is to certify that the thesis entitled "**CP Violation, Mass Hierrachy and Octant Degeneracy in Terrestrial Neutrino Oscillation Experiments**" submitted to Tezpur University in the Department of Physics under the School of Sciences in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** in **Physics** has been examined by us on .... and found to be satisfactory.

The Committee recommends for award of the degree of Doctor of Philosophy.

Signature of Principal Supervisor Signature of External Examiner

Acknowledgment

"*Kindness is the language the deaf can hear, and the blind can see.*"
- Mark Twain

I want to applaud and express my gratitude to the few people who were kind to me and helped me get through these trying times. At the outset, I would like to express my sincere thanking to my supervisor, Dr. Ng. K. Francis, for his insightful advice and on occasion, his motivation. He provided suggestions, which helped me finally develop the thesis. It would not be possible to complete this uphill journey without his unwavering support.

I am grateful to Dr. Cao Van Son, my collaborator at Institute For Interdisciplinary Research in Science and Education (IFIRSE), Quy Nhon, Binh Dinh, Vietnam for providing me with technical assistance in GLoBES to help me address the thesis' objectives. I'd also like to thank Dr. N. T. Hong Van, Mr. Tran Van Ngoc, and Ms. Phan To Quyen for our fruitful conversations. I will always be grateful to Prof. Jean Trân Thanh Vân, the President of the Rencontres du Vietnam, and the International Centre for Interdisciplinary Science and Education (ICISE), Vietnam, for taking the time to consider my request and funding my trip to Vietnam in the middle of 2019 to conduct the preliminary phase of the research.

I would like to extend my gratitude toward my doctoral committee: Prof. Jayanta Kumar Sarma and Dr. Moon Moon Devi for their critical comments throughout the tenure of my work. I also would like to acknowledge all the faculty members of Department of Physics, Tezpur University for their encouragements. The acknowledgment section would be incomplete without thanking Narayan Sarma Da, the heart and soul of all the department, in helping the research scholars with every required formalities.

I appreciate Prof. Joachim Kopp, Dr. Ananya Mukherjee, Dr. Samiran Roy, Dr. Monojit Ghosh, Dr. Mehedi Masud, and Dr. Debajyoti Dutta for answering my

emails whenever I had questions, both in theoretical and technical aspects.

I value the interactions I have with each of my physics department peers and the memorable moments we have had together on campus. For their love and support, I will always hold Mr. Animesh Barman and Mr. Bikash Thapa close to my heart. I treasure the times I spent with my senior, the late Biswa Kumar Das, the then Senior technical Assistant of the department. I'd also like to look back on my experiences at the university's Saraighat CV Raman Men Hostel (SCVRMH). One of my absolute favourite days of my life happened to occur here.

Last but not least, I want to express my gratitude to my parents, Mr. Kusheshwar Nath and Mrs. Manju Devi, my brothers, my maternal uncles, Mr. Ranjit Kumar Nath and Mr. Ratna Nath, my cousin Mr. Tarun Kumar Nath, and my extended family member Saswati Chutia for their unconditional love and willingness to share the difficult times. In times of need, my close friends Aakash, Amit, Gogo Da, Dickshit Da, and Bichita have helped me beyond expectations.

At the conclusion, I would like to express my gratitude to everyone who contributed to the thesis in some way, both inside and outside the Tezpur University fraternity. I'll end by asking the unseen power to preserve our energy so that we can devote ourselves to completing the difficult tasks ahead.

Ankur Nath

Glossary of Terms

LEP	**L**arge **E**lectron **P**ositron
VEV	**V**acuum **E**xpectation **V**alue
PMNS	**P**ontecorvo-**M**aki-**N**akagawa-**S**akata
CP	**C**harge-**P**arity
T2K	**T**okai-To-**K**amioka
NOνA	**N**uMI **O**ff-axis **N**eutrino **A**ppearance
A-LBL	**A**ccelerator-based **L**ong **B**ase**L**ine
POT	*protons-on-target*
MH	**M**ass **H**ierarchy
PVC	**P**oly**v**inyl **C**hloride
JUNO	**J**iangmen **U**nderground **N**eutrino **O**bservatory
NPP	**N**uclear **P**ower **P**lant
GW	**G**iga-**W**att
R-SBL	**R**eactor-based **S**hort **B**asel**i**ne
R-MBL	**R**eactor-based **M**edium **B**asel**i**ne
A-LBL	**A**ccelerator-based **L**ong **B**asel**i**ne
RENO	**R**eactor **E**xperiment for **N**eutrino **O**scillation
KamLAND	**Kam**ioka **L**iquid scintillator **A**nti**N**eutrino **D**etector
GLoBES	**G**eneral **Lo**ng **B**aseline **E**xperiment **S**imulator
PSE	**P**ost **S**mearing **E**fficiency
CCQE	**C**harged **C**urrent **Q**uasi-**E**lastic
NC	**N**eutral **C**urrent
MINOS	**M**ain **I**njector **N**eutrino **O**scillation **S**earch
SK	**S**uper-**K**amiokande

List of Figures

1-1 Measurements of the hadron production cross-section around the Z^0 resonance. The curves indicate the predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass [13]. 4

1-2 Natural and artificial sources of neutrino in a nutshell[20]. 7

1-3 The pp (CNO) chain of the solar thermonuclear reaction in shown in the left (right) figure. The produced neutrinos are depicted in bold fonts [21] 8

1-4 An observable electron anti-neutrino ($\bar{\nu}_e$) spectrum in reactor neutrino experiment [57]. 13

1-5 Allowed regions of $\sin^2\theta_{12} - \Delta m^2_{21}$ for fixed $\theta_{13} = 8.6^\circ$ for solar and KamLAND data, with and without Super Kamiokande results. The updated allowed regions are showed at 1σ, 90%, 2σ, 99% and 3σ C.L for 2 d.o.f.. The analysis for KamLAND is given by solid green contours with best fit marked by a green star [75]. 14

1-6 Process of neutrino production, propagation and detection in accelerator neutrino oscillation experiments. The left portion of the image is the NuMI beamline [79] which are employed in the MINOS [80], MINOS+ [81] and NOνA [82] experiments. 16

1-7 Neutrino energy as a function of the parent π-energy for different off-axis angles*(left)* and the overall predicted flux per given exposure*(right)*. The figure is a description of the NOνA experiment [83]. 19

1-8 Feynman diagrams for different types of neutrinos interactions at the detector. The image is taken from https://www.phys.ksu.edu/reu/2018/song.html. 20

1-9 The neutrino and antineutrino per nucleon CC cross sections (for an isoscalar target) divided by neutrino energy as a function of energy [103]. 21

1-10 Illustration of normal and inverted neutrino mass hierarchies. 25

2-1 Feynman diagrams of the coherent forward elastic scattering processes experienced by neutrinos on the particles in matter. . . . 59

2-2 $P(\nu_\mu \to \nu_e)$ for L =295 (*top*) and L=810 km (*bottom*) for $\delta_{CP} = -\pi/2$. 68

2-3 $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for L =295 (*top*) and L=810 km (*bottom*) for $\delta_{CP} = -\pi/2$. 69

2-4 $P(\nu_\mu \to \nu_e$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for L =295 (*top*) and L=810 km (*bottom*) for $\delta_{CP} = 0, -\pi/2$. 70

2-5 The Eight-fold degeneracy in $\nu_\mu \to \nu_e$ appearance channel for NOνA baseline. Courtesy: Son Cao [23]. 73

2-6 $P_{\mu e}(\theta_{23}, \delta_{CP}) = P_{\mu e}(\theta'_{23}, \delta'_{CP})$ Degeneracy at E_ν =0.6 GeV (T2K). . 73

2-7 $P_{\mu e}(\theta_{23}, \delta_{CP}) = P_{\mu e}(\theta'_{23}, \delta'_{CP})$ Degeneracy at E_ν=2.0 GeV (NOνA). . 74

2-8 $P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\pi/2 - \theta_{23})$ Degeneracy at E_ν =0.6 GeV for T2K(*left*) and 2.0 GeV for NOνA(*right*). 74

3-1 A Schematic diagram of J-PARC, Tokai to Super-K detector, Kamioka. Images taken from Mishima K, et al. 9th International Workshop on Accelerator Alignment, September 26-29, 2006. 80

3-2 Schematic of T2K far neutrino detector: Super Kamiokande [8]. . . 81

3-3 A graphic representation of one of the first neutrino interactions captured at the NOvA far detector in northern Minnesota. The dotted red line represents the neutrino beam, generated at Fermilab in Illinois and sent through 500 miles of earth to the far detector. The image on the left is a simplified 3-D view of the detector, the top right view shows the interaction from the top of the detector, and the bottom right view shows the interaction from the side of the detector. The information is reproduced from https://vms.fnal.gov/asset. 84

3-4 Interaction topologies for CCν_μ (*top*), CCν_e (*middle*) and NC (*bottom*) neutrino interactions [18] 85

3-5 Location of JUNO site [22]. 86

3-6 A schematic view of the JUNO detector [22] 88

3-7 Recent results of T2K experiment. The *top* figures show the reconstructed energy distribution for ν_e appearance and the *bottom* figures represent the ν_μ disappearance events. The left (right) plot shows the events in neutrino (antineutrino) mode [31] 91

3-8 Reconstructed neutrino energy spectra for the NOνA FD. The *left* figures show the reconstructed energy distribution for $\nu_m u$ disappearance and the *right* figures represent the ν_e appearance events. The top (bottom) plot shows the events in neutrino (antineutrino) mode. The appearance events are classified in three bins from lowest to highest purity: "Peripheral", "Low PID", and "High PID" [32] 92

3-9 T2K flux at far detector for antineutrino mode (left pannel) and neutrino mode (right pannel), updated in 2016. 94

3-10 NOνA Near Detector Flux. 95

3-11 NOνA Far Detector Flux normalized to 10^{20} POTs per year. 96

3-12 Expected event spectra of the signal and background as a function of reconstructed neutrino energy for T2K-II for appearance sample. The spectra are for ν-mode. Same oscillation parameters as Ref. [38] are used. 98

3-13 Same as Figure 3-12, but for $\bar{\nu}$-mode. 99

3-14 Expected event spectra of the signal and background as a function of reconstructed neutrino energy for T2K-II disappearance sample. The spectra are for ν-mode. Same oscillation parameters as Ref. [38] are used. 100

3-15 Same as Figure 3-14, but for $\bar{\nu}$-mode. 101

3-16 Expected event spectra of the signal and background as a function of reconstructed neutrino energy for NOνA-II for the appearance channel. The spectra are for ν-mode. *Normal* MH, $\delta_{\mathrm{CP}} = 0$, and other oscillation parameters given in Tab. 2.1 are assumed. 102

3-17 Same as Figure 3-16, but for $\bar{\nu}$-mode. 102

3-18 Expected event spectra of the signal and background as a function of reconstructed neutrino energy for NOνA-II for disappearance channel. The spectra are for ν-mode. *Normal* MH, $\delta_{\mathrm{CP}} = 0$, and other oscillation parameters given in Tab. 2.1 are assumed. 103

3-19 Same as Figure 3-18, but for $\bar{\nu}$-mode. 103

3-20 JUNO event rate calculated at same oscillation parameters as Ref. [22] 105

4-1 Baseline dependence on A_{CP}. The thin vertical lines show the ambiguity from the θ_{23} octant degeneracy. The positions of the intercept at $L = 0$ for $\sin\delta_{CP} = 0, \pm 1$ are shown [1] 111

4-2 Electron antineutrino disappearance probability for JUNO. 113

4-3 MH sensitivities as a function of *true* δ_{CP} calculated for various experimental setups. $\sin^2\theta_{23} = 0.5$ is assumed to be true. 118

4-4 MH sensitivities as a function of *true* δ_{CP} calculated for the joint analyses of all considered experiments but at different $\sin^2\theta_{23}$ values. 118

4-5 MH sensitivities as a function of *true* δ_{CP} calculated for all considered experiments for comparing two possible MH hypotheses. $\sin^2\theta_{23} = 0.5$ is assumed to be true. 119

4-6 Dependence of the neutrino MH sensitivity on the θ_{13} true values: $\sin^2\theta_{13} = 0.02241$ is the best fit obtained with NuFIT 4.1 [5], $\sin^2\theta_{13} = 0.02221$ is with NuFIT 5.0 [6], and $\sin^2\theta_{13} = 0.02034$ is 3σ C.L. lower limit. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be true. 119

4-7 CPV sensitivity as a function of the *true* value of δ_{CP} obtained with different analyses. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be *true*. Top (bottom) plot is with the MH assumed to be *unknown* (*known*) in the analysis respectively. 121

4-8 CPV sensitivity as a function of the *true* value of δ_{CP} obtained with a joint analysis of all considered experiments at different *true* $\sin^2\theta_{23}$ values (0.43, 0.5, 0.6). Top (bottom) plot is with the *normal* (*inverted*) MH respectively assumed to be true. 122

4-9 Dependence of the combined sensitivity on T2K-II POT exposure on MH sensitivities as a function of *true* δ_{CP} obtained with a joint analysis of all considered experiments. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be true. 123

4-10 Dependence of the combined sensitivity on T2K-II POT exposure on CPV sensitivity as a function of the *true* value of δ_{CP} obtained with a joint analysis of all considered experiments. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be true. 124

5-1 Allowed region of $\sin^2\theta_{13}$-δ_{CP} at the 3σ C.L. compared between a joint analysis of T2K-II and NOνA-II and the present constraint from the global data [4]. 130

5-2 Allowed region in the $\sin^2\theta_{23}-\Delta m^2_{31}$ space at 90% C.L. with various experimental setups. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be true. 130

5-3 Allowed region of *test* $\sin^2\theta_{23}$ at 3σ C.L as a function of *true* $\sin^2\theta_{23}$. *Normal* MH and $\delta_{\mathrm{CP}} = -\frac{\pi}{2}$ are assumed to be true. 131

5-4 Statistical significance to exclude the *wrong* octant as a function of $\sin^2\theta_{23}$. *Normal* MH and $\delta_{\mathrm{CP}} = -\frac{\pi}{2}$ are assumed to be true. 132

List of Tables

1.1 The structure of quarks and leptons in the SM. 'L' and 'R' stand for left and right-handed particles. 3

1.2 Classification of neutrino oscillation experiments with their source-detector distance (L), energy (E) and sensitivity to Δm^2_{ij}. 12

1.3 The neutrino oscillation parameters, according to two different global fits- Global Fit 1[75] & Global Fit 2[76]. 23

2.1 Global constraint of oscillation parameters with *normal* mass hierarchy assumed [18]. 67

3.1 Summary of the thermal power and baseline to the JUNO detector for the Yangjiang (YJ) reactor cores 87

3.2 Summary of the thermal power and baseline to the JUNO detector for the Taishan (TS) reactor cores. 87

3.3 Experimental specifications of the A-LBL experiment T2K-II. . . . 97

3.4 Experimental specifications of the A-LBL experiment NOνA-II. . . 98

3.5 Detection efficiencies(%)^a of signal and background events in appearance samples. Normal mass hierarchy and $\delta_{CP} = 0$ are assumed. 99

3.6 Detection efficiencies(%) of signal and background events in disappearance samples. Normal mass hierarchy is assumed 100

3.7 JUNO simulated specifications 104

4.1 Varying $\theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{31}$ for the marginalisation procedure 115

4.2 Systematics of $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance channels at the FD in T2K-II and NOνA. 115

4.3 Systematics of $\bar{\nu}_e$ disappearance channel in JUNO. 115

4.4 Fractional region of δ_{CP}, depending on $\sin^2\theta_{23}$, can be explored with 3σ or higher significance 123