Certificate

This is to certify that the thesis titled *Effect of NSI on Quantum Correlations in Neutrino Oscillation*, submitted by *Bhavna Yadav (P18PH003)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by her under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



Prof. Ashutosh Kumar Alok
Ph.D.Thesis Supervisor

Declaration

I hereby declare that the work presented in this thesis entitled *Effect of NSI on Quantum Correlations in Neutrino Oscillation* submitted to the Indian Institute of Technology Jodhpur in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Professor Ashutosh Kumar Alok. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.



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Abstract

The Standard Model (SM) of particle physics stands as our most successful framework for understanding the fundamental constituents of the universe. Within this model, neutrinos emerge as fascinating, elusive particles that were initially believed to be massless. However, the phenomenon of neutrino oscillations revealed that they actually have tiny, nonzero masses. This discovery showed that our current understanding of particle physics was incomplete and pointed to new physics beyond the SM. To delve deeper into neutrino oscillations, we need to consider potential new physics beyond the SM. One such aspect is non-standard interactions (NSI), among other new physics effects. Neutrinos, treated as a three-mode system and mapped to a three-qubit system, offer a unique avenue for exploring quantum correlations. Neutrino oscillations exhibit nonclassical traits in Bell's inequality, and they serve as an excellent candidate for testing theories of local hidden variables grounded in the principles of locality and realism.

In entangled systems like neutrinos, Bell's inequality violation has been used to measure nonlocal correlations. However, recent studies suggest that a measure called Nonlocal Advantage of Quantum Coherence (NAQC) is a stronger measure of nonlocality than Bell's inequality parameter in neutrino systems. We investigated this in two-flavor neutrino oscillations across various experiments (DUNE, MINOS, T2K, KamLAND, JUNO, and Daya Bay), considering the impact of NSI. Our findings reveal that while NAQC is a stronger measure of nonlocality, it is relatively less sensitive to NSI effects than Bell's inequality. Entanglement is another interesting feature to analyze in the neutrino oscillation system. In this work, we investigated the effect of NSI on entanglement measurements such as entanglement of formation, concurrence, and negativity for a three-flavor neutrino oscillation framework in six accelerator and reactor studies. Although it has recently been demonstrated that negativity is a weaker measure than the other two entanglement measures, we discover that negativity is more susceptible to NSI. The effect of NSI also depends on the baseline of an experiment; that's why DUNE shows more sensitivity. The recent anomaly observed in NOνA and T2K experiments in standard three-flavor neutrino oscillation could potentially signal physics extending beyond the SM. For the NSI parameters that can accommodate this anomaly, i.e., $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$, we explore the violation of Leggett-Garg type inequalities (LGtI) within the context of three-flavor neutrino oscillations. LGtI violation is significantly enhanced in normal ordering (NO) for the $\epsilon_{e\tau}$ scenario, whereas it is suppressed for the $\epsilon_{e\mu}$ scenario for T2K, NOνA, and DUNE experiment set-up for the three-flavor neutrino oscillation framework. Scalar NSI introduces a coupling between neutrinos and scalar fields, resulting in corrections to the neutrino mass term. There is a growing interest in examining the effects of scalar NSI on experiments that explore neutrino oscillations. We analyze the effect of scalar NSI on various quantum correlation measures in the DUNE experiment.

List of articles

This thesis is based on the following journal articles:

1. **Bhavna Yadav**, Trisha Sarkar, Khushboo Dixit, Ashutosh Kumar Alok, "*Can NSI affect non-local correlations in neutrino oscillations?*", Eur. Phys. J. C **82**, 446 (2022).

2. Lekhashri Konwar, **Bhavna Yadav**. "*NSI effects on tripartite entanglement in neutrino oscillations*", Nucl. Phys. B **1002**, 116544 (2024).

3. Lekhashri Konwar, Juhi Vardani, and **Bhavna Yadav**. "*Violation of LGtI inequalities in the light of NOνA and T2K anomaly*", Eur. Phys. J. C **84**, 1103 (2024).

4. **Bhavna Yadav**, and Ashutosh Kumar Alok. "*Impact of Scalar NSI on Spatial and Temporal Correlations in Neutrino Oscillations*", arXiv:2411.17503 (2024). (Under Review)

Following conference proceedings are also part of this thesis:

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2. **Bhavna Yadav**, "*NSI effects on entanglement of formation in three-flavor neutrino oscillations*", Springer Proc.Phys. 361 (2025) 131-140. Contribution to: ICFPNAP 2024.

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Acronyms

BSM	Beyond Standard Model
BNL	Brookhaven National Laboratory
CC	Charged Current
CHSH	Clauser-Horne-Shimony-Holt
CKM	Cabibbo-Kobayashi-Maskawa
CL	Confidence Level
CNO	Carbon–Nitrogen–Oxygen
CP	Charge Conjugation-Parity
CPT	Charge conjugation-Parity-Time
DM	Dark Matter
DONuT	Direct Observation of ν_τ
DUNE	Deep Underground Neutrino Experiment
EOF	Entanglement of Formation
EPR	Einstein–Podolsky–Rosen
ES	Elastic Scattering
ESSnuSB	European Spallation Source neutrino Super Beam
FCNC	Flavor Changing Neutral Currents
GALLEX	Gallium Experiment
GGM	Generalized geometric measure
GMC	Genuinely Multipartite Concurrence
IMB	Irvine–Michigan–Brookhaven
IH	Inverted Hierarchy

IO	Inverted Ordering
J-PARC	Japan Proton Accelerator Research Complex
JUNO	Jiangmen Underground Neutrino Observatory
KamLAND	Kamioka Liquid Scintillator Antineutrino Detector
LBL	Long Baseline
LEP	The Large Electron–Positron Collider
LGI	Leggett-Garg Inequality
LGtI	Leggett-Garg-type Inequality
LHC	Large Hadron Collider
LMA	Large Mixing Angle
LOCC	Local Operations and Classical Communication
LOW	Low Mass
MINOS	Main injector neutrino oscillation search
MR	Macroscopic Realism
MSW	Mikheyev–Smirnov–Wolfenstein
NAQC	Non-local advantage of Quantum Coherence
NC	Neutral Current
NH	Normal Hierarchy
NO	Normal Ordering
NIM	Non-Invasive Measurement
NOνA	NuMI Off-axis ν_e Appearance
NSI	Non Standard Interaction
NuMI	Neutrinos at the Main Injector
PMNS	Pontecorvo-Maki-Nakagawa-Sakata
POVM	Positive-Operator Valued Measure
RENO	Reactor Experiment for Neutrino Oscillation
SAGE	Soviet–American Gallium Experiment

SBL	Short Baseline
SK	Super-Kamiokande
SLAC	Stanford Linear Accelerator Center
SM	Standard Model
SMA	Small Mixing Angle
SNO	Sudbury Neutrino Observatory
SNSI	Scalar Non Standard Interaction
SO	Standard Oscillation
SSM	Standard Solar Model
T2K	Tokai-to-Kamioka
VAC	Vacuum
VEV	Vacuum Expectation Value
VNSI	Vector Non Standard Interaction

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