Effect of NSI on Quantum Correlations in Neutrino Oscillation

A Thesis submitted by

Bhavna Yadav

in partial fulfillment of the requirements for the award of the degree of

Doctor of Philosophy



Indian Institute of Technology Jodhpur
Department of Physics

August, 2024

8
Conclusions

The SM is the most successful theory in particle physics, with many of its theoretical predictions verified experimentally. Despite its success, the SM has several drawbacks, indicating that it is not the ultimate theory of nature. This suggests the existence of theories beyond the SM. Neutrinos are potential candidates for exploring such new physics. NSI provides a convenient way to incorporate new physics in the neutrino sector. Neutrino oscillation, a quantum mechanical phenomenon associated with large coherence, makes the neutrino system ideal for studying quantum correlation measures, which are valuable for both quantum information and particle physics. Quantum correlation measures can expressed in terms of neutrino probabilities and are influenced by NSI.

There are already several analyses in which various aspects of quantum correlation in vacuum are studied. Different aspects of nonclassicality for the neutrino system have been addressed in this thesis by examining the two-flavor scenario and the three-flavor scenario of neutrino oscillation. The matter and NSI effects are incorporated to conduct the study within the framework of the various reactor and accelerator neutrino experiments. Both neutrino and antineutrino for the experimental setups are considered for the study.

Initially, we study the effect of NSI on the NAQC parameter $N_{l_1}(\rho)$ as well as on Bell's inequality parameter $M(\rho)$ for two-flavor neutrino oscillations in the context of different accelerator and reactor experimental setups, i.e. DUNE, MINOS, T2K, KamLAND, JUNO and Daya Bay. Nonlocal correlations in entangled systems are usually captured by measures such as Bell's inequality violation. It was recently shown that in neutrino systems, a measure of NAQC can be considered as a stronger measure of nonlocal correlations as compared to the Bell's inequality violation. We find that even in the presence of NSI, Bell's inequality violation occurs in the entire energy range whereas the NAQC violation is observed only in some specific energy range justifying the more elementary feature of NAQC. The parameter $N_{l_1}(\rho)$ is found to show stronger evidence of quantumness as compared to the Bell-parameter $M(\rho)$. In this work, we present for the first time the inclusion of NSI in the framework of NAQC and Bell-type quantum correlation measures. We also derive the analytical expressions for both the NAQC parameter $N_{l_1}(\rho)$ and Bell's inequality parameter $M(\rho)$ in the presence of NSI.

We observe that NSI can enhance the violation of NAQC and $M(\rho)$ at higher energies in comparison to the SM and vacuum scenarios. Further, we find that NSI can enhance the violation of NAQC and Bell's inequality parameter in the higher energy range of a given experimental setup. In the case of LBL reactor experiment experiment KamLAND, this distinction is significantly visible in specific energy regions. However, the Bell-parameter $M(\rho)$ seems to be more sensitive to the new physics effects in comparison to the NAQC parameter. However, the possible enhancement in the violation of the Bell's inequality parameter over the standard model prediction can be up to 11% whereas for NAQC it is 7%. Thus although NAQC is a comparatively stronger witness of nonclassicality, it shows lesser sensitivity to NSI effects in comparison to the Bell's inequality parameter.

Quantum correlations are a multifaceted concept within the domain of quantum mechanics, and they cannot be fully described by a single quantity or measure. One of the most famous and intriguing facets of quantum correlations is entanglement. Entanglement is not a single-valued quantity; rather, numerous methods exist to quantify it. These quantification approaches include EOF, Concurrence, and Negativity. We investigate the impact of new physics on different measures of tripartite entanglement within the context of three-flavor neutrino oscillations. These measures encompass concurrence, entanglement of formation, and negativity. We analyze the influence of new physics on these measures across a range of experimental setups involving both reactors and accelerators. Reactor experiments under consideration include Daya Bay, JUNO, and KamLAND setups, while accelerator experiments encompass T2K, MINOS, and DUNE. This work is among the first to provide a comprehensive comparative analysis of how different quantum entanglement measures behave under NSI effects in three-flavor neutrino oscillations across both reactor and accelerator experiments. Our analysis reveals that accelerator experiments demonstrate greater sensitivity to NSI, with the most pronounced impact observed in the DUNE experiment. Despite entanglement of formation and concurrence being effective measures in accelerator experiments, negativity still exhibits higher sensitivity than concurrence towards NSI. Conversely, reactor experiments demonstrate less sensitivity to NSI, with concurrence and EOF displaying more prominent effects.

Recently, an 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, we explore the violation of LGtI within the context of three-flavor neutrino oscillations. Our analysis focuses on LGtI violations in scenarios involving complex NSI with $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$ coupling in long baseline accelerator experiments for normal and inverted mass ordering. By focusing on $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$, we provide new insight into how temporal quantum correlations can act as sensitive probes of physics beyond the Standard Model in long-baseline neutrino experiments. LGtI violation is significantly enhanced in NO for $\epsilon_{e\tau}$ the scenario for T2K, NOνA, and DUNE experiment setups. The degree of enhancement in K_3 in DUNE surpasses that of NOvA. However, in the case of IO, LGtI violation is enhanced for the $\epsilon_{e\tau}$ scenario over SM interaction, while LGtI violation for the $\epsilon_{e\mu}$ scenario is not affected significantly. Therefore, an interesting result of this work is that if LGtI is violated in the DUNE experiment for IO at energy above 8.5 GeV, this would be possible only for the $\epsilon_{e\tau}$ scenario. $\epsilon_{e\tau}$ scenario is favored in the context of normal ordering as well as inverted ordering.

Probability serves as a fundamental measure in experimental observations, particularly in the context of neutrino oscillation studies, where it is commonly measured. LGtI can be expressed in terms of probabilities and exhibits complementary behavior to probabilities, providing an additional avenue to study the NSI effects. Hence, by initially detecting the NSI effects through probability measurements, we can reinforce their existence through LGtI observations. This dual approach strengthens our understanding of NSI phenomena and enhances our ability to characterize their impact on neutrino behavior. One advantage is that the possible deviation of NSI from SM is more pronounced in LGtI than in probabilities.

Most of the analysis presented here pertains to vector NSI. Scalar NSI is an emerging field, and as it develops, the bounds of scalar NSI are continually improving. In response to these developments, we aim to examine the impact of scalar NSI on quantum correlation measures. This is the first study to investigate the influence of scalar NSI on quantum correlation measures, including both spatial (CHSH) and temporal (LGtI) nonlocality in the context of neutrino oscillations. This provides a novel perspective on how scalar-mediated interactions may affect fundamental quantum properties in neutrino systems. To do this, we focus on nonlocality, the strongest measure of quantum correlation, considering both spatial and temporal aspects. Utilizing the DUNE experimental

setup, we analyzed the influence of each scalar NSI parameter on quantum correlation measures. Our findings indicate that both vector and scalar NSI significantly amplify LGtI violations at higher energies, with the scalar parameter $\eta_{e\tau}$ having the most pronounced impact. Other NSI parameters showed less sensitivity, with η_{ee} being the least influential on LGtI. Around 2.5 GeV, where the DUNE neutrino flux peaks, the $\eta_{\mu\tau}$ scenario demonstrated a stronger effect. Additionally, the CHSH inequality is significantly enhanced in the $\eta_{e\tau}$ scenario.

This thesis brings together several studies to explore how NSI affects quantum correlations in neutrino oscillations. Each chapter looks at a different angle, such as two-flavor or three-flavor oscillations, spatial or temporal quantum effects, and vector or scalar types of NSI. The work focuses on different quantum measures like nonlocality parameters $M(\rho)$ and $N_{l_1}(\rho)$, entanglement (through concurrence, entanglement of formation, and negativity) and temporal correlations using LGtI. Across all cases, a common pattern emerges: these quantum measures are sensitive to NSI, especially at higher energies. This suggests that NSI can leave clear signatures in quantum behavior. Together, these results show that quantum correlations can act as useful tools to search for physics beyond the SM and can complement standard studies in neutrino physics.

While this thesis primarily focuses on how NSI, both vector and scalar, influence different quantum correlation measures in neutrino oscillations, several exciting directions remain open for future work. One promising path is to explore how quantum correlations themselves can be used to probe fundamental properties of neutrinos, such as the mass ordering and CP-violating phase. For example, the study by Dixit et al. [81] has shown that quantum correlations can be sensitive to the mass hierarchy problem, particularly in experiments like DUNE, where large baselines and high energies enhance such effects. Building on this, future research can further investigate the connection between quantum correlation signatures and the structure of the neutrino mass matrix and mixing.

Another important direction is the detailed study of scalar NSI. Unlike vector NSI, scalar NSI can directly modify the neutrino mass matrix and hence are expected to leave distinct imprints on quantum correlations. This makes scalar NSI particularly relevant for short-baseline experiments, where their effects may become more significant due to modified effective mass terms. Exploring scalar NSI induced quantum correlations across different experimental settings can help in uncovering new physics beyond the Standard Model from a quantum information perspective. These directions offer valuable opportunities for both theoretical developments and experimental applications in the field of neutrino physics.