

Conclusions

The Standard Model (SM) encompasses the fundamental interactions of nature except gravity and is the most successful theory of particle physics at present. In spite of its momentous success, there are several drawbacks in SM, which leads to the conclusion that the SM cannot be the ultimate theory of nature and hence the existence of the theory at beyond the SM is predicted. The neutrino is a potential candidate to probe such new physics (NP). The non-standard interaction (NSI) is one convenient way to incorporate NP in the neutrino sector. NSI is the model independent parametrization of the NP which considers the SM to be the lower energy effective theory of a complete theory existing at a higher energy scale. In this thesis, the effect of NSI is studied in the neutrino system at lower and higher energy regions.

Since the neutrino oscillation is a quantum mechanical phenomena that is associated with large coherence, the neutrino system has great potential for the test of quantum correlation measures which is beneficial for the quantum information sector alongwith the particle physics. The temporal and spatial correlation measures taken into account for this study can be written in terms of the neutrino flavour transition probabilities and hence, they are affected by NSI. In fact, the deviation in presence of NSI from the SM matter effect is comparatively more prominent for the quantum correlation measures than the neutrino oscillation probabilities. The correlation measures are studied in context of long baseline (LBL) DUNE experimental set up. From the recent global analysis of the data from the COHERENT (CE ν NS) and oscillation experiments, two most favourable NSI solutions are emerged namely, LMA-Light with normal mass ordering (NO) and LMA-Dark with inverted mass ordering (IO). The temporal correlation, Leggett-Garg type inequality (LGtI) studied in this work shows violation in the LMA-Dark scenario only around the energy region $\approx 3 - 4$ GeV which corresponds to the maximum flux observed at DUNE experiment. Thus, the violation of LGtI points towards a specific solution of NSI. Although the spatial correlations, namely flavour entropy and genuine tripartite entanglement also exhibit significant deviation in case of the two NSI solutions, the genuine netanglement shows the deviation more prominently.

In ultra high energy (UHE) regime, the cosmic neutrinos coming from the outer space have great potential to probe NP beyond SM. The UHE neutrinos experience scattering with the nuclei inside the Earth's atmosphere and develop air showers. In presence of large extra dimensions (LED), the fundamental Planck scale is lowered to the EW scale and the scattering of the UHE neutrino with the nuclei can generate microscopic black hole (BH) if the center of mass energy of the collision exceeds the modified Planck scale. These microscopic BHs can also develop air showers after decay and the signatures of such events exhibit distinguished features from the events produced from the standard electroweak scattering processes in the km³ neutrino telescopes like IceCube. In this thesis the effect of NSI is studied on the number of shower events in context of IceCube neutrino detector. The events generated from the decay of microscopic BH shows marginal deviation in presence of NSI as compared to the SM matter effect, showing a large enhancement of the shower event numbers, and thus eventually implying the existence of the microscopic BH.

Future direction:

- The temporal and spatial correlations studied in this thesis shows distinctive features in presence of non-standard interaction. The most interesting result is the enhanced violation of Leggett-Garg type inequality at the energy corresponding to the maximum flux observed at DUNE experimental set up only for the LMA-Dark solution of NSI. Hence, it will be interesting to test different other quantum correlation measures taking the NSI effect into account in context of the current and future long baseline experiments.
- The detection of microscopic black holes is very challenging. The microscopic black hole generates events with unique signature that might be possible to be observed at the neutrino telescopes. Such observation will help to understand the existence of new physics beyond Planck scale which is constrained by the number of extra dimensions.

6.1 Other works done

Apart from the works included in the thesis, the author has co-authored several other works. The brief description of these works are discussed below.

- *NSI effect on non-local correlation in neutrino oscillation:*

In [307], the effect of NSI is studied in two spatial correlation measures, Bell's inequality and non-local advantage of quantum coherence (NAQC) in two flavour neutrino oscillation scenario in context of several accelerator and reactor experimental setups with different baseline lengths and energy ranges. NAQC is a stronger measure of non-locality as compared to Bell's inequality which is found to be violated only in specific energy ranges unlike the Bell's inequality violation which occurs in the entire energy ranges in presence of NSI for all the experiments. Although the violation in the measures are observed in the higher energies in presence of NSI, the maximum violation is found in case of KamLAND experiment ($L = 180$ km, $E \approx 1 - 15$ MeV). The possible enhancement in the violation of the Bell's inequality parameter over the Standard Model prediction is about 11% , whereas for NAQC it is 7%. This implies lesser sensitivity of NAQC to NSI as compared to Bell's inequality, despite of NAQC being the stronger measure of non-classicality.

- *Spin flip precision in magnetized white dwarf:*

The work done in [308] is based on the study of the neutrino spin flavour precession (SFP) in the presence of non-zero magnetic moment of neutrino. The study of SFP phenomena is useful to distinguish between the Dirac and Majorana nature of neutrino. Since the SFP phenomena is highly dependent on the magnetic field in the system, the white dwarf (WD), which is a compact star with large magnetic field, is selected for this study. The potential of the WD system is explored to study the SFP phenomena. It is found that a magnetized WD with standard parametrization is a suitable environment for this analysis and it can distinguish the Dirac and Majorana nature of neutrino from the comparison of their spin oscillation probabilities significantly. The spin flavour transition probability is found to be much higher in case of Dirac neutrinos, as compared to the Majorana neutrinos. The sensitivity of the transition probability with a range of magnetic moment values is also examined.

- *Study of thermal properties in magnetized neutron star core:*

The study of thermal evolution of the neutron star (NS) is an interesting field which helps to probe the nature of the internal matter composition and the structure of these compact objects at extreme conditions (*e.g.* high temperature, magnetic field and matter density). To understand the concept of NS cooling, the thermal properties, such as heat capacity and

thermal conductivity, are of great importance which are highly dependent on the behaviour of the interior matter. In ref. [309], these two thermal properties are studied considering two isolated model NSs with different masses and radii with their core matter with *npe* configuration governed by DDME2 equation of state (EoS) considering the effect of both the superfluid matter and large magnetic field ($\sim 10^{16} - 10^{18}$ G). This results in a non-uniform behaviour of the thermal properties all throughout the star, depending on the strength of the superfluid pairing. While the heat capacity is lowered in presence of superfluidity, the presence of non-zero proton pairing gap can enhance the neutron thermal conductivity. The results are obtained for both normal nuclear matter and considering the effect of superfluidity for a comparative analysis and illustrated at two different times ($t = 100$ & 1000 years) during the thermal evolution.

- *Fast neutron star cooling in light of PREX-2 experiment:*

The nuclear symmetry energy and its behaviour with the nuclear matter density play a crucial role in the construction of the EoS for NS matter. Recently its value is updated and is found to be enhanced than the previous estimation, based on the measurements of nuclear skin thickness observed by the PREX-2 collaboration. With the updated constraints of the symmetry energy and its slope, the cooling of NS is studied in the ref. [310]. It is found that with the modified values of symmetry energy parameters, even the lower mass stars ($\approx 1.2 M_{\odot}$) can undergo fast cooling via direct URCA (DURCA) process, which usually occurs only in case of massive stars ($\approx 2 M_{\odot}$) in the standard and minimal cooling paradigm. By comparing the cooling curves obtained in this analysis with the available observation data, it is found that the thermal profile of the most of the isolated NSs is compatible with the cooling curve associated with the canonical mass star ($1.4 M_{\odot}$) that incorporates the effect of superfluidity.