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Nuclear Effects and Standard Three Neutrino Physics

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ABSTRACT: Standard three neutrino oscillation physics is in an era of precision. Most of the parameters required to address the oscillation physics have been determined with utmost accuracy. Present and future Neutrino oscillation experiments are aiming to explore new physics. Here we have re-examined the three neutrino oscillation physics in presence of nuclear effects. The inclusion of nuclear effects in the three neutrino physics framework will change the obtained bounds and may be in some cases , can hint towards fake new physics signals.

KEYWORDS: Three neutrino physics, New Physics, Nuclear Effects, Fake Signals.

I. INTRODUCTION

The nuclear effects need to be mentioned while examining the neutrino nucleon cross sections[1][2]. Main detectors used to trace the signatures of neutrinos are Calorimetric detector, Cherenkov light detectors, Liquid Argon/ noble gas detectors and Radiochemical detectors. Neutrino cross sections are small and depends on, the target material with which the neutrino will interact, type of neutrino interaction (NC or CC) and the energy of the neutrino. Most of the ongoing and upcoming neutrino beam experiments i.e MINOS,T2K, NovA, K2K and DUNE, have a broad band neutrino energy spectrum. In general their energy lies in the range of 0.1-20 GeV. Neutrino scattering at these intermediate energies are not well measured, a large uncertainty in total scattering cross sections and energy distribution of secondary particles is observed. Several distinct scattering processes takes place at these energies i.e. QE interaction, Resonance and DIS.

The neutrino beams produced in the neutrino oscillation experiments are not mono-energetic because they are produced as the secondary decay products. The physics of neutrino oscillation experiments depends on the neutrino oscillation probability which in turn depends on the energy of neutrino. A general probability equation of neutrino of flavor αgoing to flavor βcan be written as

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2 2\theta sin^2[1.27\Delta m^2(L/E)] \quad (1)$$

Where E is the neutrino energy. The measurement of neutrino oscillation parameters requires accurate prediction of neutrino energy [3][4] . An inaccurate estimation of neutrino energy will lead towards wrong estimation of probability and hence incorrect estimation of bounds on neutrino parameters. In QE charged current neutrino scattering process the energy and the direction of the outgoing lepton provides the information regarding neutrino energy. The neutrino cross section calculated in this manner shows discrepancy from the experimental result[5][6]. The reason behind it is assumed to be neglected nuclear effects or final state interactions[7]. A number of studies have illustrated the impact of nuclear effects on neutrino oscillation studies[8][9]. In this work we have checked the three neutrino oscillation physics in absence and presence of nuclear effects and analyzed the impact that final state interactions and multinucleon interaction will impart on the event distribution of T2K[1][2][10].

II. RELATED WORK

IMPACT OF NUCLEAR EFFECTS

Generally in the neutrino nucleon scattering process$\nu + N \rightarrow l + N' + \pi^{+,0}$, the nucleon N is considered to be free. In an attempt to investigate the nuclear effects, which takes places in the experimental targets, we will have to study a

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modified reaction for the above reaction$\nu + N \rightarrow l + X' + \pi^{+,0}$, where$X'$ is an unobserved final nuclear stage particle in the above scattering. From the above equations we can conclude that the bound nucleons inside the nucleus will have multiple implications on the physics studies; (1) increased participation of many particle correlation; (2) in order to be observe the particle produce in the scattering process, the particle has to come out from the nucleus and hit the detector; (3) the initial and final state densities gets modified. Therefore we conclude that in order to reconstruct the neutrino energy accurately from the scattering process we must have an definite idea of final state interactions[6]. If the neutino energy is reconstructed by CCQE (charged current quasi-elastic), the inclusion of these final state interactions will help us to differentiate between QE events and QE like events. This filtering will help us in better estimation of neutrino energy. In our work neutrino nucleon final state interactions are included using software GiBUU[11] for T2K experiment.

III.STUDY OF CCQE INTERACTIONS, USING GIBBU

The Giessen-Boltzmann-Uehling-Uhlenbeck (GiBUU), incorporates best possible information of nuclear interaction in one consistent theory. Using GiBUU we can generate inclusive cross sections as well as full final state events.
Since the charged lepton produced in the final state can be readily observed by the detectors, CCQE interactions are often studied for the reconstruction of the neutrino energy. In CCQE events the reconstruction of neutrino energy needs the kinematic variables of observed charge leptons. In absence of nuclear effects the number of events generated by neutrino of neutrino energy$E_i$can be estimated as:

$$N(E_i)^{QE} = \sigma_{qE}(E_i) x P_{\alpha\beta}(E_i) x detectorefficiency x \phi(E_i)$$

In heavy targets nuclear effects plays a dominant role due to which the outcoming particle may give us an impression of interaction being QE whereas in reality it can be resonance or something else, these events are categorized as QE like events. The QE like events are those events in which the initial particles generated in neutrino nucleon interaction are not due to QE interactions but here since the initially produced particle is not able to come out of the nucleus the finally leaving particle give us the impression of interaction being QE. The initially produced particles: (1) can be absorbed;(2) can be scattered; (3) can exchange electric charge with the nucleon;(4) can decay. A good control on final state interactions is very important Number of QE like events generated by neutrino of energy$E_i$can be estimated as:

$$N(E_i)^{QElike} = \sigma_{qE}(E_i) x P_{\alpha\beta}(E_i) x detectorefficiency x \phi(E_i) + \sigma_{nonqE}(E_i) x P_{\alpha\beta}(E_i) x detectorefficiency x \phi(E_i)$$

In this work we have selected T2K experimental setup to quantify the impact of nuclear effects on parameter determination. The T2K experiment sends an intense neutrino beam from Tokai to Kamioka at a distance of 295 Km in japan. This experiment uses two detectors: near detector and far detector. The mass of far detector is 22.5 Kiloton. A 2 degree off axis beam is used in this setup. The neutrino beam operating at power level of 0.77 Mega Watt is used. The analysis in this paper for two running years of experiment.

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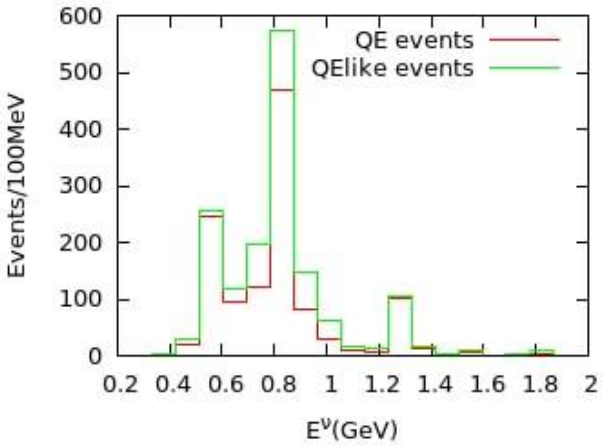

Fig. 1 The figure shows the event distribution pattern as a function of neutrino energy. The red line shows the distribution of QE events and the green line shows the event distribution pattern for QE like events.

IV. SUMMARY AND CONCLUSIONS

Over the past few years the data collected by different running and completed, neutrino oscillation experiments have lead us to a better understanding of neutrino nucleon interactions in broad spectrum of energy. The excess of CCQE events reported by MiniBooNE collaboration [12], whose explanation within RFGM requires a large increase in the nucleon axial mass in comparison to that obtained from the deutron data, is capable of assigning some process other than the single nucleon knock out [13] . Complete description of impact of nuclear effects is not possible since in neutrino oscillation experiments deals with large momentum transfer, which makes nonrelativistic approaches impractical.

The study of the impact of nuclear effects or final state interactions on the determination of neutrino oscillation parameters is still in budding stage [14]. As heavy targets used in the neutrino oscillation experiments hence a careful study of these effects are required in the next phase of neutrino studies. From the Fig.1 we can observe that the event distribution with neutrino energy changes as soon as we consider nuclear effects in our studies. This change in distribution will towards determination of neutrino oscillation parameters inaccurately. In present era neutrinos as supposed to be the one of the potential candidate to probe physics beyond the standard model or new physics. In this case the uncertainty in the neutrino oscillation parameter can mislead the standard model signal as the signal from new phsics.

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