Impact of Nuclear Effects on Neutrino Oscillation Results

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ABSTRACT *Neutrino oscillation physics is one of potential candidate to answer many unresolved mysteries of particle physics, Astrophysics and Cosmology. Most of the parameters of neutrino oscillation physics have been determined with high precession. Running and future neutrino oscillation experiments use heavy targets and hence role of nuclear effects cannot be ignored. All the neutrino oscillation results need to be re-examined in the presence of nuclear effects. Here in this work we have estimated the impact of nuclear effects on the estimation of neutrino oscillation physics parameter.*

Keywords:*Nuclear Effects, neutrino oscillation, oscillation parameters, impact.*

I. INTRODUCTION

While estimating the neutrino nucleon cross sections the nuclear effects must be taken into consideration [1][2]. The uncertainty in the determination of cross section will lead towards the uncertainty in the neutrino oscillation results. Neutrino cross sections are small and depends on the energy of the interacting neutrino, type of neutrino interaction like charged current or neutral current(NC or CC) and the material of the target. Few ongoing and upcoming neutrino beam experiments are MINOS,T2K, NovA, K2K and DUNE. The neutrino beams of these experiments have a broad spectrum, their energy lies in the range of 0.1-20 GeV. Neutrino scattering at these intermediate energies are not well measured. In this region a large uncertainty in total scattering cross sections and energy distribution of secondary particles is observed. Several neutrino scattering processes takes place at these energies and their cross section needs to be determined accurately.

The neutrino beams are produced as secondary decay products in the neutrino oscillation experiments and are not mono-energetic. The physics of neutrino oscillation experiments depends on the neutrino oscillation probability which is a function of neutrino energy. A general probability equation of neutrino produced as flavor and detected as flavor can be given as

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

Where L is the distance between the source and detector, is mixing angle and 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 estimate the probability incorrectly and this will lead towards incorrect estimation of bounds on neutrino parameters. Neutrino energy can be estimated by looking at the kinematics of the outgoing lepton in quasi-elastic charged current process (CCQE).The neutrino cross sections calculated in this manner shows discrepancy from the observed experimental result[5][6]. The reason behind this discrepancy can be assigned to the negligence of the 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 of final state interactions on the event distribution of NOvA[1][2][10]. The CCQE interactions are examined in this work.

II: Impact of Nuclear Effects

A neutrino nucleon scattering process can be represented as $\nu + N \rightarrow l + N' + \pi$, here the nucleon N is considered to be free. The nuclear effects study, which are dominant when neutrino interacts with heavy experimental targets needs a modified form reaction $\nu + N \rightarrow l + X' + \pi$ to be expressed, where is an unobserved final nuclear stage particle in the above scattering. From the above equations we can observe that the bound nucleons inside the nucleus will have multiple implications on the physics studies, few of them are; (1) participation of many particle correlation; (2) the particles which get absorbed in the nucleus, 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 neutrino scattering processes we must have an definite idea of final state interactions[6]. If the neutrino energy is reconstructed by CCQE (charged current quasi-elastic) interactions, the inclusion of these final state interactions will help us to differentiate between QE events and QE like events. This filtering will help us to get pure QE events and with this set of events will help us in better estimation of neutrino energy. In our work neutrino nucleon final state interactions are included using software GiBUU[11] for NOvA experiment.

II.

III. Study of CCQE Interactions At NOvA, using GiBUU

The Giessen-Boltzmann-Uehling-Uehlenbeck (GiBUU) which is based on Boltzmann-Uehling-Uhlenbeck (BBU) equation is a flexible tool for numerical simulation of nuclear reactions. It 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.

The kinematics of charged lepton produced in the final state can be easily observed by the detectors hence CCQE interactions are often studied for the reconstruction of the neutrino energy. For CCQE events the reconstruction of neutrino energy depends only on the momentum and angle of out-coming leptons. In absence of nuclear effects the number of events generated by neutrino of neutrino energy can be estimated as:

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

In heavy targets nuclear effects plays a dominant role and many a times the out coming particle may give an impression of interaction being QE whereas in reality it is not QE. That interaction can be resonance or something else and the particle generated during the initial interaction was not able to come out of the nucleus, these events are categorized as QE like events. The initially produced particles can participate in different phenomenon while traveling inside the nucleus : (1) they can be absorbed;(2) they can get scattered; (3) they can exchange electric charge with the nucleon;(4) they can decay. A good control on final state interactions is very important Number of QE like events generated by neutrino of energy can be estimated as:

$$N(E_i)^{QElike} = \sigma_{qE}(E_i) \times P_{\alpha\beta}(E_i) \times \phi(E_i) \text{Migration Matrix of QE}$$

$$+\sigma_{nonqE}(E_i) \times P_{\alpha\beta}(E_i) \times \phi(E_i) \text{Migration Matrix of Non QE}$$

These migration matrix are generated with the help of GiBUU.

In this work we have selected NOvA experimental setup to quantify the impact of nuclear effects on parameter determination. The NOvA experiment have NuMI (Neutrinos at main

Injector) neutrino off-axis beam. This beam consist mostly of .This experiment can probe $\nu_\mu(\overline{\nu_\mu}) \rightarrow \nu_\mu(\bar{\iota}$disappearance and $\nu_\mu(\overline{\nu_\mu}) \rightarrow \nu_e(\bar{\iota}$appearance channel. This experiment uses two detectors: near detector and far detector. The far detector has 14 KT mass and is placed at a distance of 810 Km from the source. Here in our studies we are using $\nu_\mu \rightarrow$ channel.

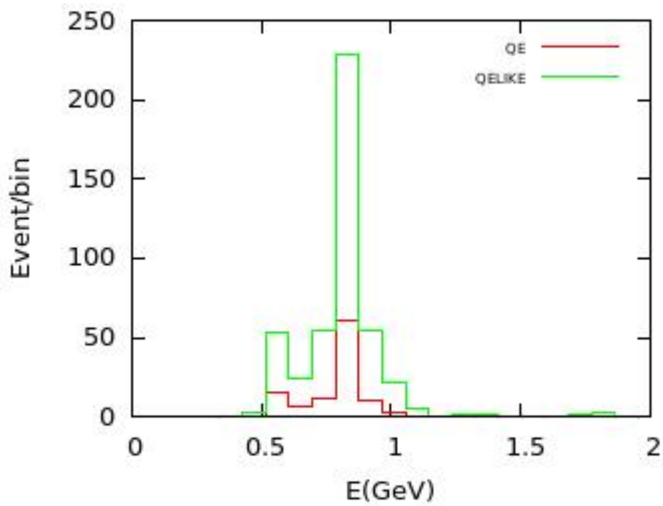

Fig. 1 The figure shows the event distribution pattern of QE and QE like events/bin as a function of neutrino energy. The red line shows the distribution of QE events and the green line shows the event distribution pattern for QE like events.

From Fig. 1 we can observe that there are sufficient contribution of QE events in the total CCQE events observed by NOvA. The incorrect estimation of total CCQE events will towards incorrect estimation of neutrino energy.

V. SUMMARY AND CONCLUSIONS

The experimental data collected over the past few decades have helped us in developing a better understanding of neutrino nucleon interactions in broad spectrum of neutrino energy. The MiniBooNE collaboration [12] reported excess of CCQE events, and the explanation tothese excess events 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 non relativistic 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]. Neutrino oscillation experiments use heavy targets and the study neutrino interactions with heavy target nucleon will need a careful study of nuclear effects. The understanding of these nuclear effects are required in the next phase of neutrino studies. In absence of nuclear effects many fake QE events will be considered as QE events and this sample of QE event will have some intrinsic error. This error will be propagated in the estimation of different neutrino parameter. From the Fig.1 we can observe that the nuclear effects incorporation while studying the neutrino nucleon interaction is important in order to generate a pure QE event sample. 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 estimation of neutrino oscillation parameter can mislead the standard model signal as the signal from new physics.

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