Recent Results from the MINERνA experiment

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In the era of the fastest-growing technology in the field of particle accelerators and detectors, the scope of neutrino physics is expanding very rapidly. The neutrino oscillation parameters are being measured with a higher degree of precision. The precision of these oscillation parameters directly depend on the neutrino-nucleus cross section measurements done by various experiments with multiple nuclear targets. One of these few experiments is the MINERνA, a dedicated neutrino-nucleus interaction experiment at Fermilab which took data from 2009 to 2019 for both neutrino and antineutrino scattering in the low-energy and medium energy peaking around 3 GeV and 6 GeV, respectively. This article will cover some recent inclusive measurements from the MINERνA experiment. These results will provide a strong basis for future experiments like DUNE and help in improving the measurement of neutrino oscillation parameters.

1. Introduction

Neutrinos have proven to be one of the important sources to probe the fundamental aspects of physical reality. They are the second most abundant particles after photons in the universe and least understood, thus, a better understanding is crucial in order to understand different physics phenomena associated with the neutrinos. The precision measurement of the oscillation parameters of neutrinos is done using the neutrinos from the accelerators, nuclear reactors. One of the important oscillation parameters, the Dirac CP-violating phase, may be present in the neutrino flavor mixing matrix [1, 2, 3, 4], is associated with the mysterious matter-antimatter asymmetry in the universe and can be explained by the measurement of a non-zero Dirac phase. Neutrino experiments are considered to be one of the potential sources of studying beyond Standard Model (BSM) physics such as light dark matter and heavy neutral leptons [5, 6]. In order to achieve higher statistics, most of the present and future neutrino oscillation experiments are using moderate to heavy nuclear targets, therefore, we need to understand how a neutrino interacts with a nucleus. But, given the fact that neutrino sources are not mono-energetic, these energy-sensitive interactions are convolved with the neutrino flux, causing major systematic uncertainties in precision measurements.

The neutrino-nucleus interactions are affected by the nuclear medium effects and, as a matter of fact, we don't have a model of complete nuclear response in neutrino-nucleus interactions in the few-GeV regime of incident neutrino, the comprehensive ν-A measurements are required to guide the development of models. This is where MINERνA (Main INjector ExpeRiment for ν-A) comes into the picture as a dedicated experiment to understand the effects between hadronic and nuclear degrees of freedom in ν-A interactions and to measure different aspects of intranuclear dynamics prerequisite for precision measurement of neutrino oscillation parameters.

In order to correct for detector and nuclear effects, oscillation experiments [8, 9, 10, 11] depend on neutrino interaction models. These experiments plan to use an inclusive charged current (CC) signal to maximize far detector statistical precision and energy resolution. The precise measurement of the angular distribution and the momentum of the charged lepton is necessary in order to correct the measured rate for efficiency and acceptance in both near and far detectors. The neutrino energy is reconstructed using neutrino interaction models as an input so any mismodeling

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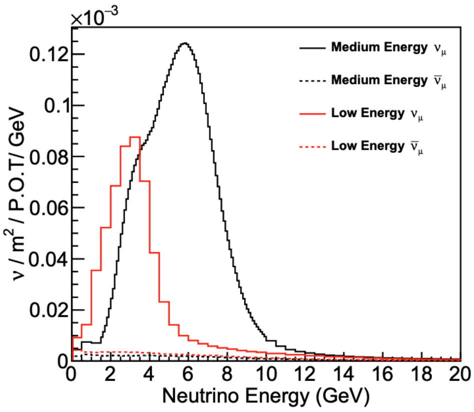

FIG. 1: Low and Medium Energy fluxes in the neutrino focused mode along with the contaminations at MINERνA.

of charged lepton energy will affect the neutrino energy reconstruction. In past, many experiments like MicroBooNE [12], T2K [13], NOMAD [14], MINOS [15], CCFR [16], K2K, etc. have done inclusive cross section measurements on a variety of nuclear targets. MINERνA has made similar kind of measurements as a function of neutrino energy on carbon for both neutrino and anti-neutrino beams [17, 18] and as a function of muon transverse (p_t) and longitudinal ($p_{||}$) momentum in the low energy (LE) NuMI beam with a neutrino flux peaked at 3 GeV [19]. The results shown here are measured as a function of muon transverse and longitudinal momentum in the medium energy (ME) of NuMI beam with flux peaked around 6 GeV. The advantage of this analysis from the previous result is the sample is around 12 times larger and flux normalization uncertainty is approximately half the size of the previous result. The low energy and medium energy fluxes used by MINERνA are shown in Figure 1.

The variables like muon momentum and angle can be precisely measured hence, are suitable for comparison to exclusive measurements and makes a solid foundation to understand model predictions. The description of the experiment is covered in section II and the simulation of the neutrino interactions, modifications to models, etc are covered in Section III. Section IV briefly describes the analysis procedure to get the final cross sections. A brief description of the systematic uncertainties used in the analysis is done in Section V. Section VI provides conclusions drawn from the results.

2. MINERνA Experiment

Neutrinos are created by the interaction of 120 GeV protons with the graphite target at Fermilab's NuMI beamline. The pions and kaons created due to the interaction of protons on the graphite target are focused on by two magnetic horns. By changing the polarity of these magnetic horns, a neutrino or antineutrino-dominated beam is obtained. These neutrinos/anti-neutrinos then travel and interact with the MINERνA detector, which is a fine-grained tracking detector consisting of 280 active hexagonal planes made up of triangular strips. It has two main regions an active tracker region [20] and a nuclear target region hosting a number of different nuclear targets like iron, lead, carbon, helium, and water. The active tracker region has a fiducial mass of 5.48 tons. The detector is surrounded by electromagnetic and hadronic calorimeters. The fiducial volume is comprised of 88.5% carbon, 8.2% hydrogen, 2.5% oxygen, 0.5% titanium, 0.2% chlorine, 0.07% aluminum, and 0.07% silicon by mass. In a high multiplicity region for a better three-dimensional reconstruction, planes are oriented in three different directions, 0 and $\pm 60°$ relative to the vertical axis of the detector. Wavelength-shifting fibers embedded in the scintillators are read by optical cables connecting to photomultiplier tubes which read out the scintillations with a 3-ns timing resolution. The side and downstream electromagnetic calorimeters contain alternating layers of scintillators and 2mm thick lead planes while the downstream and side hadronic calorimeters contain alternating scintillators and 2.54 cm thick steel planes.

Downstream of the MINERνA detector sits