Component study of the NuMI neutrino beam for NOνA experiment at Fermilab

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1. Introduction

The neutrino beam, NuMI, from Fermilab's Main Injector accelerator is the most intense neutrino beam in the world. The experiment NOνA will use this neutrino beam to study neutrino oscillation where neutrino of a given flavor oscillates into another flavor. The oscillation is parameterized by the PMNS mixing-matrix and the mass squared differences between the three masses. Thus, there are six variables that affect neutrino oscillation: the three mixing angles θ_{12}, θ_{23} and θ_{13}, a CP-violating phase δ, and two mass-differences. The angles θ_{12} and θ_{23} have been measured to be non zero by several experiments. In 2012, the last angle, θ_{13}, was measured at Daya Bay/Reno to be non zero to a statistical significance of 5.2σ [1]. No measurement of the CP-violating phase, δ has been made. Furthermore, whereas the absolute values of two mass square differences are known, the ordering of the masses has not been determined. By observing these neutrino oscillations, NOνA hopes to accomplish some of the most important scientific goals of neutrino physics such as more sensitive measurements of 2→3 oscillation and θ_{13}, measurement of CP-violating phase δ, determination of neutrino mass hierarchy, etc.. For this, NOνA will use two 14mrad off-axis detectors, a 330 metric ton near detector at Fermilab and a 14 metric-kiloton far detector in northern Minnesota. The detectors are made up of extruded, highly reflective plastic PVC cells filled with liquid scintillator [2].

2. Off - Axis Location of Detectors

NOνA has located its detectors slightly off the centerline. This off-axis location produces a large neutrino flux that peaks at 2 GeV, the energy where oscillation to electron neutrinos is expected to be maximum. The relative narrowness of the off-axis beam aids in rejecting backgrounds to the electron neutrino appearance search. Fig. 1 shows the effect on neutrino energy spectrum for progressively larger off-axis angles. On-axis, the beam produces a neutrino flux peaked at 7 GeV [2].

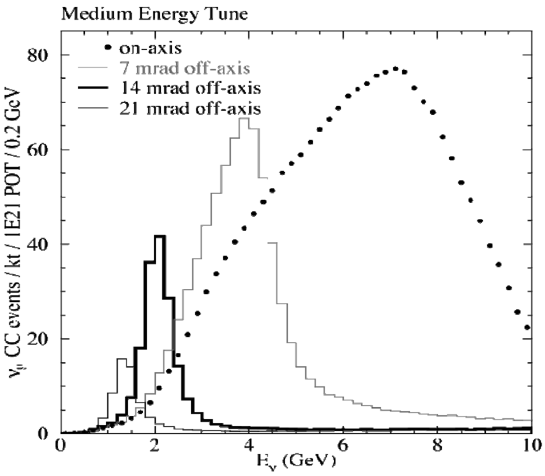

Fig. 1 Neutrino event rates as a function of energy and off-axis angle.

3. Production of NuMI Beam

The first step in the production of the tertiary NuMI beam is to direct a beam of 120 GeV protons from Fermilab's Main Injector onto a primary target i.e. Carbon. Interactions of the proton beam in the target produces secondary mesons, primarily pions and kaons, which are focused toward the beam axis by two magnetic horns. The mesons then decay to muons and neutrinos during their flight through a long decay tunnel. A hadron absorber downstream of the decay tunnel removes the remaining uninteracted protons and undecayed mesons from the beam. The muons are absorbed by a subsequent Earth shield, while the neutrinos continue through it to the NOνA near detector onsite at Fermilab, then through 810 km of Earth to the far detector [3]. Table 1 shows the NuMI beam parameters for NOνA.

Proton beam power	0.7 MW
Proton energy	120 GeV
Repetition rate	1.33 sec.
Protons per spill	4.9×10^{13}

Table 1: Beam parameters for NOνA.

4. Results of NuMI Beam Simulation with G4NuMI

Flux simulation of NuMI beam line is performed using G4NuMI package. The energy spectrum and the composition of the beam are measured at both the detectors. Table 2 shows the percentage production of the beam components at the near detector (Simulation with Geant4.9.6p01a and FTFP_BERT hadron production model). The most abundant neutrino flavor in NuMI beam is ν_μ. Fig. 2 and Fig. 3 show the character of neutrino yield / 10^7 POT in the NuMI beam at near and far detector respectively.

Neutrino Flavor	% (Production)
ν_μ	65.6
$\bar{\nu}_\mu$	32.1
ν_e	1.5
$\bar{\nu}_e$	0.7

Table 2: Percentage production of NuMI beam components at NOνA near detector.

The most significant energy interval for consideration is 0.4 GeV to 5.4 GeV as a large fraction of neutrinos in the NuMI beam have energy in this interval. In this energy range 87.4% of ν_μ are produced via decay of π^+ through channel (i) and 11.9% of ν_μ are produced via decay of K^+ through channels (ii) and (iii). A negligibly small fraction of ν_μ comes from K_L^0 and μ^- parents via channel (iv) and (v) respectively.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{(i)}$$
$$K^+ \rightarrow \mu^+ + \nu_\mu \quad \text{(ii)}$$
$$K^+ \rightarrow \mu^+ + \pi^0 + \nu_\mu \quad \text{(iii)}$$
$$K_L^0 \rightarrow \mu^+ + \pi^- + \nu_\mu \quad \text{(iv)}$$
$$\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu \quad \text{(v)}$$

The most dominant ν_μ parents, π^+, have their origin in various beam elements like Carbon (primary target), Helium, Steel, Concrete, Decay Pipe Vacuum etc. Of all π^+ producing ν_μ at the near detector 88.9% originate in the primary target Carbon, 2.9% in M1018 Steel, 1.9% in Helium and a very small fraction of π^+ have their origin in other beam elements.

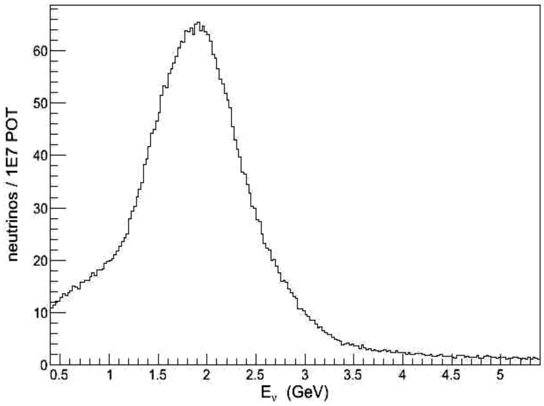

Fig. 2 Energy Spectrum of NuMI beam at NovA near detector.

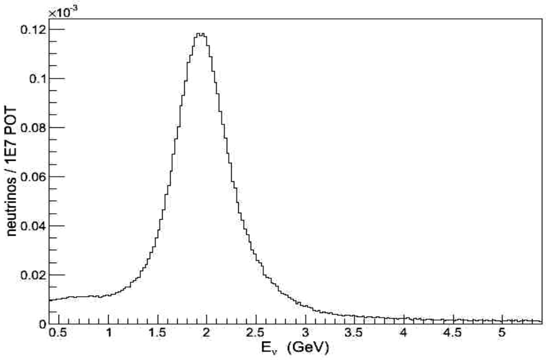

Fig. 3: Energy Spectrum of NuMI beam at NovA far detector.

Acknowledgments

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