The MINER\nu\nA Neutrino Scattering Experiment

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Abstract. MINER\nu\nA is a neutrino scattering experiment at the NuMI beamline of FNAL, which began data taking in fall 2009. MINER\nu\nA is a high resolution, fully active detector designed to study the interaction of neutrinos with nuclei. The active volume of the detector consists of 3 tons of plastic scintillator. In addition, targets of \n\nHe, C, H\n\n2\n\nO, Fe, and Pb will allow detailed studies of the A dependence of neutrino cross sections. Some of the objectives of MINER\nu\nA are to measure the axial form factor of the neutron with unprecedented precision, measure nuclear shadowing of F\n\n2 and compare with muon scattering, study quark-hadron duality with neutrino scattering in comparison with electron scattering, and measure coherent pion production. We present an overview of the physics objectives, estimated uncertainties of the measurements, along with a description of the detector and a sample of the first measurements.

1. Introduction

In order to study neutrino oscillations, Fermi National Accelerator Laboratory (FNAL) constructed the Neutrinos at the Main Injector (NuMI) beamline. In addition to its role of providing neutrinos for oscillation studies, this extremely high intensity neutrino beam opens new possibilities for studying neutrino scattering with unprecedented detail. The Main Injector Experiment \nu-A (MINER\nu\nA) was designed to take advantage of this opportunity. The detector is a compact, good resolution, fully active detector which will study neutrino interactions on a variety of nuclei. The detector is placed upstream of the MINOS detector, which serves a muon spectrometer for MINER\nu\nA, in the NuMI hall.

2. The MINER\nu\nA Detector

A schematic of the MINER\nu\nA detector is show in Fig. 1. The detector consists of five main regions: the fully active central detector, the upstream nuclear targets, a downstream electromagnetic and hadron calorimeter, and a surrounding electromagnetic and hadron calorimeter.

The central detector serves as both the primary target and the tracking detector. It consists of planes of triangular plastic scintillator strips arranged in three orientations, as shown in Fig. 2. Each strip is 1.7 cm high and 3.3 cm wide, and is read out via a wavelength shifting fiber, as shown in Fig. 3. Light sharing between the strips gives a position resolution of approximately 3 mm. The light yield is approximately 6.5 photo-electrons/MeV, giving about 24 photo-electrons/plane for minimum ionizing muons.

The downstream electromagnetic calorimeter consists of alternating planes of 2 mm thick Pb and scintillator planes of the same form as in the central detector. The hadron calorimeter is similar, with 2.5 cm planes of steel instead of Pb. The side electromagnetic calorimeter consists of 2 mm thick Pb plates between every other tracking plane in the outer region of the central detector. The side hadron calorimeter consist of planes of steel with scintillator strips embedded, as shown in Fig. 2.
Upstream of the central detector are planes of passive targets, with two planes 2.5 cm thick of mixed Fe/Pb, one plane with 2.5 cm thick Fe/Pb and 7.5 cm C, 15 cm thick H$_2$O, a solid plane of Pb 0.75 cm thick, and a mixed plane of Fe/Pb 1.5 cm thick. The mixed Fe/Pb planes are split with part of the plane being iron and part of the plane being lead, such that the total mass is approximately equal. Tracking planes are placed between each plane of passive targets. Finally, upstream of the main detector, a tank of liquid $^4$He about 1 m in diameter will be installed in late 2010. The fiducial mass within an 85 cm radius cylinder for the solid targets is 3 tons of scintillator, 0.4 tons of C, 0.9 tons of Pb and Fe, 0.3 ton of H$_2$O. The fiducial mass for $^4$He is approximately 0.25 ton.

Charged current events originating in the central detector are fully contained, except for the muon, for neutrino energies less than 10 GeV. The MINOS detector gives both muon energy and charge for forward going muons. For other particles, particle identification can be determined from the dE/dX, but there is no charge determination.

**Figure 1** Schematic of the MINERvA detector.

**Figure 2** Front view of the detector showing plane orientation and outer calorimetery.

**Figure 3** Section of a tracking plane showing individual strip shapes and readout fiber location.
3. Rates and Schedule
The current run plan is to have $16 \times 10^{20}$ protons on target (POT), with a mix of the NuMI low energy configuration, which have an average neutrino energy of about 4 GeV, and the medium energy configuration, which has an average neutrino energy of 8 GeV. The detector was completed in March 2010 with NuMI in the low energy configuration, and it is anticipated to continue in the low energy configuration until early 2012, with about $4 \times 10^{20}$ POT. The current plan is for shutdown of the NuMI line from spring 2012 through spring 2013 for upgrades to the NuMI facility for NOvA. For 2013-2016 NuMI is anticipated to run in the medium energy configuration and provide MINERvA with an additional $12 \times 10^{20}$ POT.

For the combined low and medium energy runs, the estimated number of charged current interactions in $^4$He, scintillator, C, H$_2$O, Fe, and Pb to be 0.6 M, 9 M, 0.4 M, 0.7 M, 2.9 M, and 2.9 M, respectively. There will be a large sample of neutral current events equal to about $\frac{1}{2}$ the CC sample. These values do not include any correction for muon acceptance (for CC), tracking efficiency, etc., so analyzable event numbers will be less. In addition, an initial run with about half the detector in place, in the antineutrino mode was made between October 2009 and March 2010.

4. Detector Performance
We have collected a considerable amount of data with the partial detector running in the antineutrino mode, and with the full detector in the neutrino mode. We have been studying the detector performance and characteristics. Our analysis to date shows that the detector is working well and meets our design specifications. Of the 31,000 channels in the full detector, greater than 99.9% are working, as shown in Fig. 4. We have been successful in matching muons seen in MINERvA with their downstream tracks in MINOS. As shown in Fig. 5, the angle vs. energy distribution of muon energies is reasonable, and about as expected.

![Figure 4](image1.png)

**Figure 4** Occupancy plot showing number of hits per channel.

![Figure 5](image2.png)

**Figure 5** Muon scattering angle vs. momentum for muons detected in both MINERvA and MINOS.
5. Physics Goals

Apart from the interest in the intrinsic properties of neutrinos explored by oscillation experiments, neutrinos can serve as a probe of the properties of the nucleon. They are unique as probes in that they are the only ones that have flavor sensitivity. Combining neutrino and antineutrino scattering allows determination of parton structure function. Because neutrinos only interact weakly, they are the ideal probe to determine the weak charge structure of nucleons. This is in contrast to electron scattering experiments, which require very precise parity violation experiments.

Although neutrinos would otherwise be an ideal probe, numerous experimental difficulties have limited their use. Their small interaction cross section requires massive detectors, even with the high beam intensities now available. The NuMI beam has a broad energy range, with a long tail reaching up to 100 GeV, and the incoming neutrino energy is not directly known for any particular reaction, rather it must be determined as the sum of visible energy of the interaction products. Neutral current interactions are even more problematic in that neither incident nor scattered neutrino energy is known.

Despite these difficulties we can still make meaningful measurements of neutrino reactions, especially charged current reactions. MINERνA will be able to study several topics including: The precision measurement of cross sections and the nuclear dependence of cross sections; the axial form factor and its A dependence; quark-hadron duality, complementing JLab experiments; search for x-dependent nuclear effects.

One of the prime goals of MINERνA is the measurement of the axial form factor of the nucleon. The basic reaction is $\nu n \rightarrow \mu^- p$, which is the most easily identified exclusive final state. The measurement on scintillator (carbon) will provide unprecedented statistical precision to high $Q^2$. The anticipated statistical precision, including estimated efficiency and acceptance corrections, from the full run, are shown in Fig. 6. The value of the extracted form factor may be influenced by final state interactions or efficiency in identifying the QE final state. In addition to conventional effects, Saito et al [6] have predicted a medium modification of the form factor of a few percent. In addition to the high precision measurement from reactions in the central detector, we will also be able to study the extraction of the form factor from oxygen, iron and lead. We anticipate we will have better than 1% statistical precision in the $Q^2 < 1 \text{ GeV}^2$ region, so systematic corrections will be the limiting factor in the comparison.

![Figure 6](image_url)

**Figure 6** Anticipated statistical precision on extraction of the axial form factor, including estimated efficiency and acceptance corrections. The dashed line shows are prediction for $F_A$ from Ref. [1]. Previous measurements are from Refs. 2-5.

Other nuclear effects are anticipated to be different between neutrino scattering and the scattering of other leptons. For example, shadowing of $F_2$ is predicted to be different for neutrino scattering and...
muon scattering, Kulagin [7], as shown in Fig. 7. The shadowing depends on the nucleus, and will cause the extracted $F_2$ to be different for different nuclei. MINERνA will be able to make precision comparisons between carbon, iron, and lead at a level that will test these models.

![Figure 7](image)

**Figure 7** Comparison of shadowing effects of lead compared to carbon as a function of energy loss for neutrino and muon scattering, from Ref. [7], with anticipated statistics from MINERνA for the four year run.

In addition, to these, MINERνA will be able to study a number of reactions in detail. Coherent pion production, a potentially significant background to oscillations will be measured with significantly higher precision than previous measurements, and the nuclear dependence will be measured for the first time. We anticipate over 40K neutral current events and about 90K charged current events. The bulk of the interactions will lead to resonant pion production, with about 1.7 M events, and deep inelastic scattering, with about 4 M events. Again, MINERνA will also be able to study the A dependence of these reactions in detail for the first time.

6. Conclusions
MINERνA offers a new opportunity to study neutrino reactions with an unprecedented precision. The axial form factor will be measured to high $Q^2$ and with sufficiently high precision to study nuclear effects on it. The A dependence of coherent pion production will be measured for the first time. The initial data indicate the detector meets specifications. The full detector has been running since March 2010. The first physics results should appear in 2011.

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