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MINERνA*

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The world is entering an era of precision neutrino measurements. This requires a precise knowledge of cross sections, final states, and nuclear effects. Neutrino cross sections are poorly known, with a $\sim$ 20 to 100 percent total error [G. Sam Zeller, private communication]. There also exist unresolved discrepancies in various cross section and nuclear effects measurements. MINERνA [`http://minerva.fnal.gov/`] is an accelerator-based neutrino experiment, located at Fermi National Accelerator Laboratory, United States. MINERνA is designed to perform cross section and nuclear effects measurements with unprecedented accuracy, reducing the current errors to 5 to 20 percent total. These measurements are vital for upcoming and planned experiments such as T2K [`http://jnusrv01.kek.jp/public/t2k/`], NoVA [D. Ayres, `hep-ex/0503053`], and DUSEL [`http://www.int.washington.edu/DUSEL/`]. No other experiment exists or is planned that will be able to perform these measurements in the MINERνA energy range. MINERνA is in the final stages of construction, and will begin taking data in early 2010.

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1. The NuMI neutrino beam

Fermi National Laboratory (Fermilab), produces neutrinos at two beamlines: the Booster and NuMI. MINERνA is located in the NuMI beamline, where a 120 GeV beam of protons is directed on to a graphite target. This interaction produces a stream of mesons ($\pi^{\pm}$, $\mathrm{K}^{\pm,0}$) that decay to produce a neutrino beam. The target is located immediately upstream of two magnetic focusing horns. The horns focus positively or negatively charged mesons, allowing experiments on the NuMI beam-line to collect data using a neutrino or an anti-neutrino beam.

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The focusing horns direct the charged mesons into a decay pipe that is 675 meters in length. Immediately following the decay region is a hadron absorber composed of aluminum, steel, and concrete. This removes any undecayed mesons and non-interacting protons from the beam. An additional absorber comprising 240 meters of rock stops muons produced by the meson decay. Figure 1 illustrates the complete neutrino beam production path in the NuMI beam-line.

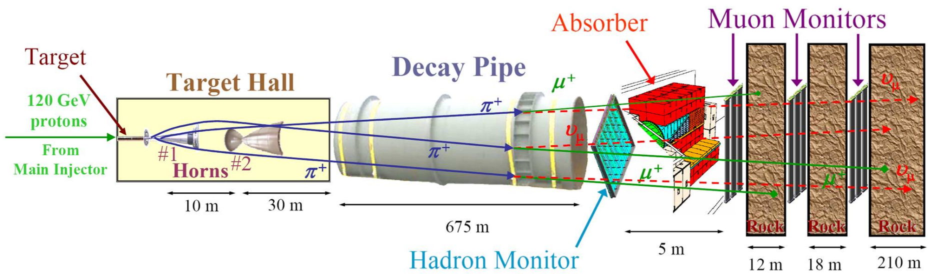

Fig. 1. The NuMI beam-line [1].

NuMI's unique system of a movable horn and target allows the neutrino beam to be configured into three different settings: low-energy (LE), medium-energy (ME), and high-energy (HE). The peak energy of the neutrino beam is 3.0 GeV in LE, 7.0 GeV in ME, and 12.0 GeV in HE. Switching between the different neutrino beam configurations takes several months. MINERνA expects to switch between configurations only once during the five years of data collection. MINERνA will collect data in the LE configuration for a total of 4e20 POT, and in the ME configuration for a total of 12e20 POT.

2. The MINERνA detector

MINERνA's goal of high-precision cross-section measurements demands a detector that is able to reconstruct and identify exclusive final states. The detector must have high granularity for charged particle tracking and identification. Low momentum thresholds for particle detection are also needed, for example, to detect the proton in charged-current quasi-elastic (CCQE, $\nu_\mu n \rightarrow \mu^- p$) interactions. The detector should also contain electromagnetic showers from neutral pions and $e^\pm$, high momentum hadrons ($\pi^\pm$ and protons), and CCQE events well enough to measure the $\mu^\pm$ momentum. The inclusion of a variety of nuclear targets enables a study of nuclear effects.

The MINERνA experiment encompasses three separate components: a veto wall, a cryogenic liquid helium target, and the MINERνA detector. The neutrino beam first encounters a veto wall composed of one inch thick steel and scintillator paddles. The veto wall protects the detector from low-energy gamma rays, and provides timing information for any residual muons in the neutrino beam. Immediately downstream of the veto wall is a 0.25 ton liquid helium target, followed by the MINERνA detector. It is approximately 5.2 meters from the veto wall to the far end of the MINERνA detector. The MINOS near detector is located 2 meters downstream from the end of the MINERνA detector, and is used by MINERνA as a muon catcher (see Fig. 2).

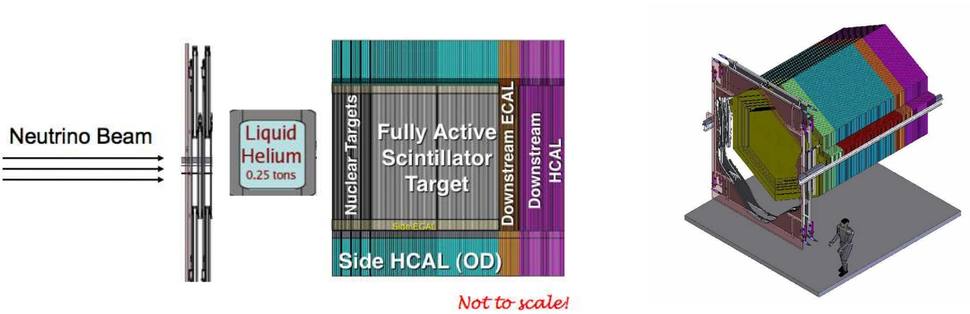

Fig. 2. Left: Side view of the MINERνA experiment. Right: Three dimensional view of the MINERνA detector.

The MINERνA detector is composed of a series of nuclear targets, fully active scintillator target, and electromagnetic and hadronic calorimeters (ECAL and HCAL, respectively). The detector is constructed from a series of hexagon-shaped modules that hang on a rack, in a similar fashion to file folders.

The main body of the MINERνA detector consists of modules with an inner detector (ID) and an outer detector (OD). The ID is made up of planes constructed from strips of fully active scintillator. There are three possible orientations for the planes of scintillator, providing three-dimensional tracking: vertical (X), rotated −60 degrees from vertical (U), and rotated +60 degrees from vertical (V). One module contains two planes in a UX or VX orientation. The ID is surrounded by the side ECAL, or 2 mm lead plates interspersed with scintillator bars. The OD surrounds and comprises the frame for the ID. The OD is the side HCAL sub-detector, and is made of iron plates and scintillator towers.

There are five nuclear targets in the detector. They are shown in Fig. 3. The first two targets, composed of iron and lead at different orientations, allow for a high statistics comparison of interactions in these two materials. The third target allows us to compare interactions in iron, carbon, and lead using the same detector geometry. The fourth target, a thin lead slab, serves to insure good photon detection efficiency. Finally, the last target allows us to study low energy particle emission. There are four scintillator frames

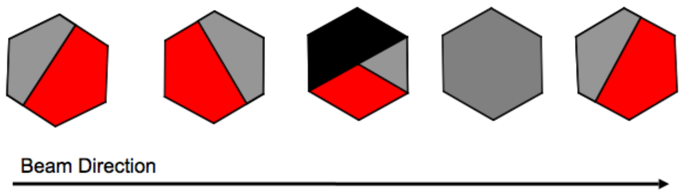

Fig. 3. Geometry of the nuclear targets in MINERνA. The targets are stacked in the detector in the order shown, from left to right. Four scintillator modules are placed between each target. Deep gray (red): Fe, grey: Pb, black: C.

(UX VX UX VX) between each of the targets. Following the nuclear target portion of the detector there are 60 fully-active tracking modules, 10 ECAL modules (15 tons), and 20 HCAL modules (30 tons).

2.1. Detector response

The precision measurements proposed by MINERνA require a thorough understanding of the detector response. For this purpose, MINERνA has developed a tracking prototype (TP) and a test beam setup.

The TP consists of several full-sized components: a single iron target, 10 scintillator-tracking modules, 10 ECAL modules, and 4 HCAL modules. The tracking prototype allows us to study neutrino interactions in the scintillator in a simple environment, with only one nuclear target. It provides a fully integrated test of all detector systems including detector design and assembly, component production and integration, the calibration chain, and event reconstruction. As of February, 2009, the TP is collecting cosmic ray data. It will be installed into the NuMI beam-line in March of 2009. Data collection in the neutrino beam will continue to the June 2009 shutdown of the accelerator complex at Fermilab.

The test beam studies are performed in the MTest Hall at Fermilab. There an 8 GeV beam of pions is sent through a system of a target, wire chambers, time of flight triggers, and magnets, before entering a partial MINERνA detector. This beam-line produces 1–10 GeV/c^2 particles. A new beam has been designed by MINERνA that will produce particles of momentum down to 200 MeV/c^2. The MTest detector is made up of pieces of scintillator planes, lead, and iron, in an easily reconfigurable system. This allows us to emulate different parts of the MINERνA detector. This system is used to benchmark the MINERνA detector response to single particles such as charged pions and kaons.

3. Analysis goals

MINERνA will perform several cross-section measurements: accurately measuring the axial form factor (F_A) of the nucleon over a wide range of four-momentum transfer (Q^2), producing statistically significant measurements of atomic mass dependence in coherent pion production, and resonance pion production in both CC and neutral-current (NC) neutrino interactions.

In addition to cross-sections, MINERνA has a comprehensive program of analyses including strange particle production, nuclear effects, parton distribution functions, and generalized parton distributions.

3.1. Quasi-elastic analysis

CCQE events are the primary channel used in oscillation analyses. The current theoretical uncertainty on CCQE cross-sections is 20%, largely due to uncertainty in nuclear effects. MINERνA will be the first experiment to systematically study F_A in the range of Q^2 from 0 to 5 GeV^2, and to systematically study the CCQE cross-section across a range of atomic mass in the same experimental environment. MINERνA is sensitive to three models of F_A: the dipole approximation (the current assumption), the constituent quark model [2], and the duality model that says the dipole approximation breaks down at Q^2 of 0.5 GeV^2. MINERνA expects to collect >800K CCQE events in the scintillator target. MINERνA will reduce the total error on this cross-section measurement to 5%.

3.2. Coherent pion production

In coherent pion production, the neutrino scatters from the entire nucleus and leaves the nucleus intact. MINERνA will produce the first measurement of the atomic mass dependence of these events, across a wide atomic mass range. MINERνA will collect 89K CC events and 44K NC events in this channel. This will increase the world's current sample size by at least a factor of 100. We expect to reduce the current error on these events from 100% to 20%.

Recent surprising results from K2K and SciBooNE [3] found no evidence for coherent production in the region of neutrino energy (E_ν) < 1.5 GeV. This result is in conflict with predictions from the Rein–Sehgal model, which fits experimental data well at higher E_ν. MINERνA's high statistics sample over a wide range of E_ν will help to elucidate this discrepancy.

3.3. Resonant production

In resonant production, the neutrino scatters from the nucleon, a nucleon resonance is excited, and it decays back to ground state via emission of one or more mesons. MINERνA will study nuclear effects and atomic mass dependence for these multi-π final states, reducing the current error from 40% to 5% (CC) and 10% (NC). We expect to collect 1.7M of these events.

3.4. Nuclear effects and deep inelastic scattering

Nuclear effects in deep inelastic scattering (DIS) have been thoroughly studied using beams of leptons (muons and electrons), but not neutrinos. This effect will be studied by measuring the cross-section and structure functions F_2 and xF_3 in the nuclear target data. The individual parton distribution functions (PDF) extracted from these events will be ones for bound protons. The measured PDFs will be compared to free-proton PDFs to extract heavy target correction factors. Neutrino scattering data provides an additional piece of information unavailable in the lepton scattering data. A recent analysis suggests that there is tension internal to existing neutrino–Fe data [4]. Nuclear correction factors for neutrino–Fe (CC) and charged lepton–Fe scattering (NC) appear to differ in their behavior as a function of Bjorken x, $x_{\rm Bj}$. Resolving this issue is essential not just for neutrino experiments, but for high-energy collider experiments that will make use of the neutrino nuclear data to develop free-proton PDFs at very high $x_{\rm Bj}$ [5]. MINERνA will collect 2.1 M events in the transition region from resonance to DIS, and 4.3 M events in the DIS region. We expect to reduce the cross-section error on DIS events from 20% to 5%.

4. Conclusions

MINERνA is poised to produce vital high-precision measurements needed as input to high-precision neutrino experiments upcoming and planned, such as T2K, NoVA, and DUSEL. MINERνA will begin data collection in early 2010.

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