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THE MINERνA EXPERIMENT*

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The poor precision of neutrino–nucleus scattering data has become a driving component of the systematic error budgets of new long-baseline oscillation experiments. By building an active detector designed to make use of the high-intensity neutrino beams developed for oscillation experiments, higher precision studies of neutrino scattering processes can be undertaken. MINERνA, a compact, fully-active detector has been proposed to employ the NuMI beam at Fermilab, and will be able to dramatically improve the statistical precision of measured scattering cross-sections. It will also be instrumented to study, in detail, the effects of the nuclear medium on neutrino physics processes.

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1. Introduction

The need for high-precision neutrino scattering data has become paramount with the advent of new, long-baseline neutrino oscillation experiments [1]. With these experiments, such as MINOS, come high-intensity neutrino beams. By constructing a compact, multi-ton, fully-active detector package which can make use of these high-intensity beams, neutrino scattering processes can be studied to higher precision than ever before. The MINERνA detector proposed and designed to run along with the MINOS near detector at Fermilab — is just such a device.

Fig. 1 shows the available neutrino scattering total cross-section data up to approximately 200 GeV incident neutrino energy. The precision of the cross-section data at moderate energies (~ 1 to ~ 20 GeV) is very poor, and this is one of the driving systematic uncertainties in precision oscillation

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measurements [1]. Together with the NuMI beam, the MINERνA detector will be able to dramatically improve the quality of the data in the $E_\nu \sim$ 1–15 GeV energy regime.

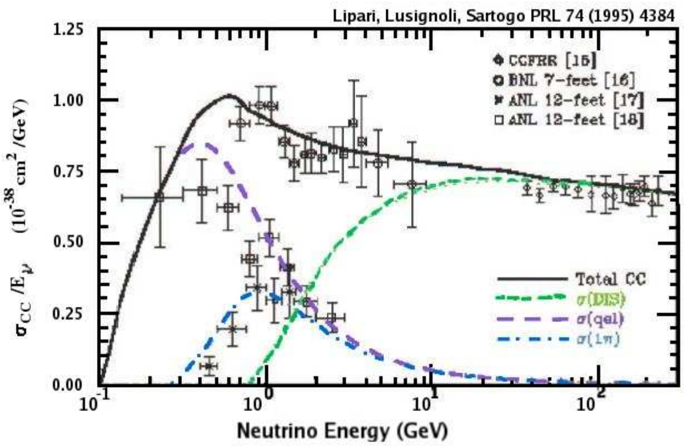

Fig. 1. Total cross-sections for ν_μ scattering. Figure from Ref. [2], with data from the references therein as labeled in the figure. The E_ν region for the NuMI beam is illustrated by the arrows in the figure.

Fig. 2 shows the improvement in both precision and Q^2-range that can be achieved in measurements of the axial form-factor, $F_{\mathrm{A}}(q^2)$. This form-factor is best accessible through neutrino–nucleon quasi-elastic scattering. The quasi-elastic cross-section is governed by a nucleon–nucleon current:

$$\langle p|J_\lambda|n\rangle = \bar{u}\Bigg[\gamma_\lambda F_{\mathrm{V}}^1(q^2) + i\sigma_{\lambda\nu}q^\nu \frac{\xi F_{\mathrm{V}}^2(q^2)}{2M} + \gamma_\lambda\gamma_5 F_{\mathrm{A}}(q^2) + q_\lambda\gamma_5 \frac{F_{\mathrm{P}}(q^2)}{M}\Bigg]u\,. \quad (1)$$

In Eq. (1) the form-factors $F_{\mathrm{V}}^{1,2}(q^2)$ are extracted from electron–nucleon elastic scattering data, and the term involving $F_{\mathrm{P}}(q^2)$ in the cross-section is small for $E_\nu > 0.2$ GeV. With the projected precision, discernment between a dipole-like Q^2 dependence and a fall-off in Q^2 similar to the behavior of $G_{\mathrm{E}}^P(Q^2)/G_{\mathrm{M}}^P(Q^2)$ as extracted from polarization transfer measurements in electron scattering at JLab [3] can be made.

Coherent single pion production is an important background process in neutrino oscillation experiments, particularly $\nu_\mu \to \nu_e$ oscillations. Typically in coherent production, the produced pion follows the path of the incident

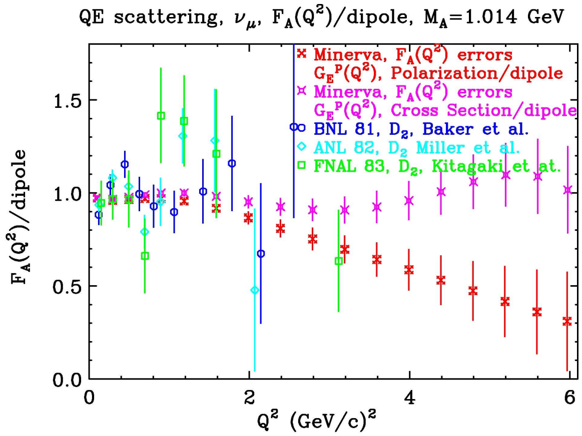

Fig. 2. Expected statistical precision for the axial form-factor from the MINERνA experiment. The errors are plotted on the expected Q^2 behavior for a dipole-type form-factor and a form-factor which exhibits the Q^2 dependence found in JLab polarization transfer measurements for $G_E^p(Q^2)/G_M^p(Q^2)$. Previous data are from Ref. [4]

neutrino, or nearly so. This pion can look like a single-electron shower, the signature of a $\nu_\mu \to \nu_e$ oscillation [1]. MINERνA detector will both improve the precision of the coherent single-pion production cross-section (Fig. 3(a)), and expand the A-range over which the process is measured (Fig. 3(b)). Together this experimental information will be beneficial in further understanding the physics of neutrino-induced coherent pion-production.

The processes available for study by the MINERνA detector are not limited to the vital quasi-elastic scattering and coherent pion production. Resonance production, the transition from resonance to deeply-inelastic scattering, and the lower energy regime of deeply-inelastic scattering are also accessible by MINERνA. Improvements in the precision of these cross-sections are crucial to improving systematic uncertainties in the new neutrino oscillation experiments. The effects of the nuclear medium on neutrino interactions are also critically important. The MINERνA detector will be instrumented to study these in detail. Examples of systematic error improvements achievable are shown in Fig. 4. The proposed improvement in Δm^2, as measured at MINOS (Fig. 4(a)), is a result of the improved assessment of the incoming neutrino energy. High precision cross-sections and nuclear medium effects are both needed for this improvement. For proposed measurements of $\sin^2(\theta_{13})$ at NOνA (Fig. 4(b)) the effect on the systematic error comes from more complete understanding of the background processes, a direct result of improved cross-section measurement [1].

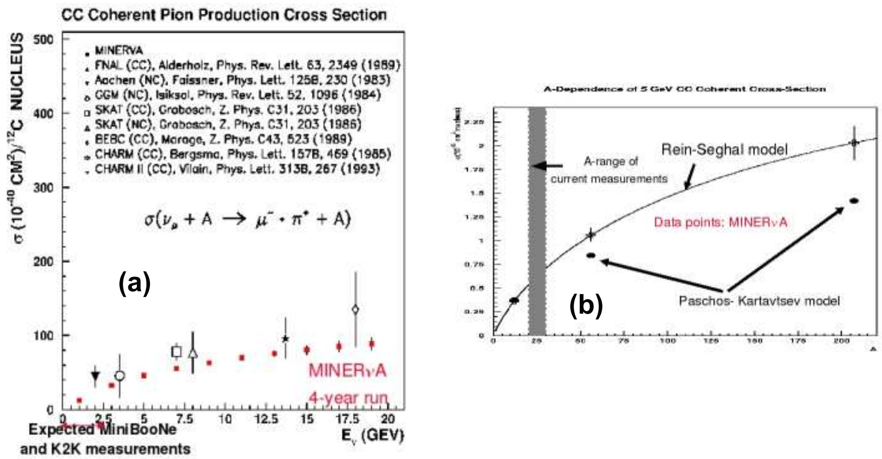

Fig. 3. Estimated improvement in precision for coherent single pion production in neutrino scattering. Notice that the MINERνA data will significantly increase the energy range of available data (a) and the A-region and production models [5, 6] explored (b).

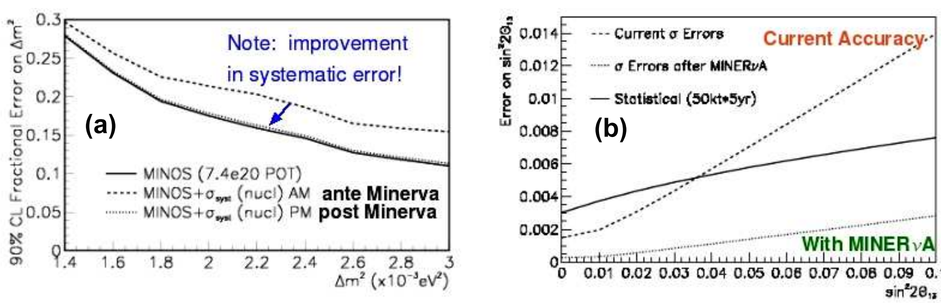

Fig. 4. Effect of increased precision in total cross-section data on the systematic error for neutrino-oscillation measurements for Δm^2 (a) and $\sin^2(\theta_{13})$ (b).

2. The MINERνA detector

The MINERνA detector is a compact, fully-active device designed to make use of the wide-band, high-intensity NuMI beam. It will be located in the MINOS near detector hall at Fermilab, just upstream of the near detector (Fig. 5(a)). Because of its compact size (~ 4 m long), the MINERνA experiment also plans use the spectrometer capabilities of the MINOS near detector for highly energetic muons. The combined functionality of the MINERνA–MINOS pair will allow unprecedented precision in studies of neutrino-nuclear interactions.

Fig. 5(b) shows the three energy spectra (in GeV) for the NuMI beam. Energies range from $E_\nu \sim 1\,\mathrm{GeV}$ to $E_\nu \sim 15\,\mathrm{GeV}$ depending upon the tune. The NuMI beam intensity is approximately 10^3 times higher than previously available [7]. The energy range and intensity allows for studies from the quasi-elastic to the deeply-inelastic scattering regime.

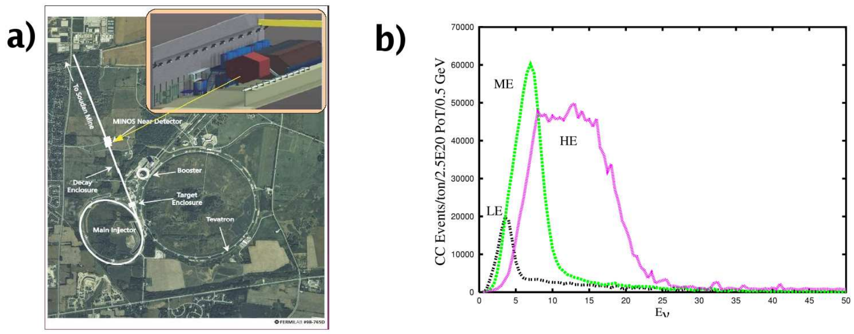

Fig. 5. The location of the MINERνA detector in the MINOS near detector hall at Fermilab (a) and the three neutrino beam energy spectra (b).

The structure of the MINERνA detector is modular, allowing for tremendous flexibility if needed. The various sections (see Fig. 6) are constructed from basic elements. Fig. 6(b) shows the "building block" of the MINERνA detector. Each plane is made of two components (a) sheets of segmented polystyrene scintillator for detection and tracking and (b) a surrounding iron and scintillator hadronic calorimeter. No part of the detector is magnetized.

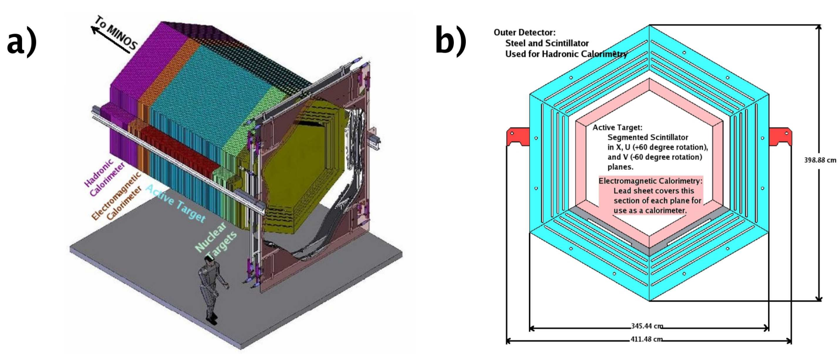

Fig. 6. (a) A schematic drawing of the MINERνA detector. The detector is segmented into various parts as labeled in the figure. The detector is approximately 4 m wide by 4 m long. (b) A schematic of a single plane within the MINERνA detector.

The "inner" detector is divided into four sections: (a) nuclear targets, (b) active target, (c) electromagnetic calorimeter, and (d) hadronic calorimeter, working from upstream (away from MINOS) to downstream (Fig. 6(a)). Each section is constructed from a combination of the active scintillator planes and an absorbing material. The absorbing materials which will be used are:

- lead sheet (nuclear target)
- iron (hadronic calorimetry, nuclear target)
- lead–steel alloy sheet (electromagnetic calorimetry)
- carbon (graphite, nuclear target).

First, the active scintillator planes are constructed from titanium dioxide/polystyrene co-extruded triangular strips 3.3 cm at the base by 1.7 cm high. Each strip has a hole made during the extrusion process for a 1.2 mm diameter wavelength-shifting fiber to be inserted (Fig. 7). These strips are organized, in 2 layers, into hexagonal planes 64 strip-wide (approx 211 cm) across for a total of 128 strips per plane. These planes are the basis for the remainder of the detector.

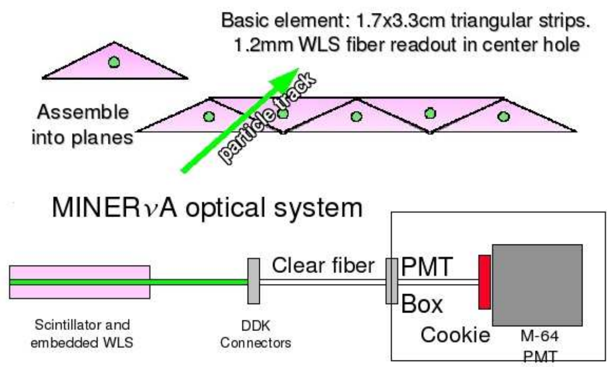

Fig. 7. Schematic layout of the scintillator strips which make up an active panel. Lower figure schematically depicts the connection of the wavelength-shifting fibers to the multi-channel photo-tube.

The basic "composite" unit of the MINERνA detector is a tracking module. This is a package of four scintillator planes arranged in an x–u, x–v configuration. Because the inner detector planes are hexagons, a rotation of $+60°$ (u) or $-60°$ (v) is convenient and, with the x-planes, generates the necessary coordinates for three dimensional tracking. Absorber material can be inserted between each plane, pair, or tracking module as needed.

The upstream most section of the MINERνA detector is reserved for nuclear targets. These targets will be made from arrays of carbon, lead, and iron sheet. The total mass of each absorber (target) are approximately 1.2 tons. These arrays are interleaved with scintillator planes for vertex reconstruction.

The second section is the active target. This section contains 120 scintillator planes organized into 30 tracking packages. Each active target plane is ringed by a lead–steel alloy electromagnetic calorimetry section (Fig. 6(b)). This sheet is 0.2 cm thick and covers 12% of the plane area.

The active target is followed by the electromagnetic calorimeter. This section is made of three tracking modules (x–u, x–v pairs). Each scintillator plane is interleaved with an 0.2 cm thick lead-steel alloy sheet covering the entire active area. The electromagnetic calorimeter has 12 sheets of absorber.

The final section of the inner detector is the hadronic calorimeter. It is similar in design to the electromagnetic calorimeter; the key difference is the iron absorber. The hadronic calorimeter has five tracking modules, each scintillator plane covered by a 2.54 cm iron sheet. The hadronic calorimeter has 20 iron sheets.

The entire inner detector is surrounded by the "outer detector", an iron-scintillator hadronic calorimeter. Each section of the hexagonal frame of the outer detector contains four machined slots for scintillator bars. The inner detector and outer detector together requires more than 25 000 channels to be read out.

The anticipated charged current event rates (and neutral current for coherent pion production) are summarized in Table I. For four years of running

TABLE I

Summary of event rates in the MINERνA detector for a four year run with the NuMI beam at Fermiab.

Charge current topic	Expected statistics
	3 Tons (fiducial) of polystyrene
Quasi-elastic	0.8 M
Resonance	1.6 M
Transition: resonance to DIS	2 M
DIS and structure functions	4.1 M
Coherent pion production	85 K CC/37 K NC
Nuclear target (fiducial masses)	
0.6 Ton carbon	1.4 M
0.5 Ton lead	1.4 M
0.5 Ton iron	1.4 M

in predominately medium-energy mode, approximately 13 million events will be collected in the MINERνA detector. More than half of these events will be in the active target polystyrene (approximately 3 tons fiducial mass). Approximately 1.4 million events are expected from each of the nuclear targets, yielding an excellent event sample.

3. Summary

The MINERνA experiment is designed to measure neutrino-nuclear interactions to high precision. The compact, segmented, fully-active detector together with the NuMI beam at Fermilab will be able to extend both the precision and the Q^2 range of quasi-elastic and coherent neutrino interactions relative to present values. The neutrino energy range available from NuMI will also allow for investigations in the resonance to deeply-inelastic scattering regime. An array of heavy nuclear targets will provide the means to investigate the effect of the nuclear medium on neutrino interactions. The improved precision of scattering cross-sections together with the studies of nuclear medium effects will dramatically improve the systematic error budget of new long-baseline neutrino oscillation experiments.

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