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Present Status of the MINOS experiment

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Abstract. The MINOS experiment will study neutrino oscillations occurring in a neutrino beam produced at Fermilab and interacting 735 km away in a large detector placed in the Soudan Underground Laboratory. The present status of construction of the experiment will be described as well as the design and goals of the experiment.

1 Introduction

The MINOS (Main Injector Neutrino Oscillation Search) Experiment will study neutrino oscillations in a high intensity neutrino beam produced at Fermilab. A 980-ton "Near" detector will measure interactions near the point of neutrino production on the Fermilab site and a much larger 5.4-kton "Far" detector, located in the Soudan Underground Laboratory in northern Minnesota will measure interactions after the beam has traveled a distance of 735 km. The beam trajectory is indicated in Fig. 1. The detectors are tracking calorimeters composed of alternating layers of steel and plastic scintillator. The experiment has been designed to provide accurate measurements of the neutrino oscillation parameters over a range consistent with the anomalies previously observed in the relative rates of atmospheric electron- and muon-neutrino interactions when they interact in underground detectors.

The neutrino beam is produced by the 120 GeV proton beam of the Main Injector at Fermilab; this is a very high intensity proton synchrotron which is used to produce the intense proton and antiproton beams needed for the latest series of collider experiments. In order to aim at Soudan, the beam must point into the earth at an angle of 58 mrad below the horizontal, requiring extensive civil construction at the Fermilab site, where the tunnel to accommodate the beam will be almost 1 km in length.

At the Soudan site a new experimental hall which will be occupied by the 8–m wide octagonal Far Detector has already been excavated, adjacent to the existing Soudan-2 nucleon decay detector. This hall is 700 m below the surface, reducing the flux of cosmic ray muons by a factor almost 10^6 from the flux at the surface. (The Soudan 2 detector itself, which has been in operation for more than a decade, will not be used in the initial phase of the MINOS experiment and, indeed, is in the process of being "mothballed" for the immediate future.)

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Fig. 1. Trajectory of the beam between Illinois and Minnesota.

2 Production of the neutrino beam

The availability of a very high intensity neutrino beam has been made possible with construction of the Main Injector at Fermilab. This accelerator operates at an energy of 120 GeV and most of its intensity is available to generate the neutrino beam in pulses of 8 μs length every 1.9 s.

The neutrino beam is produced by decay of the secondary mesons produced when the extracted beam is incident on a cooled graphite target. A selected momentum range of these mesons is focused using a system of two magnetic horns which can be moved so as to provide 3 possible wide-band beams with momenta in the ranges of approximately 2-4, 4-8, and 8-16 GeV/c. The mesons decay in a 675 m long by 2 m diameter drift space. Downstream of the drift space aluminum/steel absorbers will remove the residual flux of charged hadrons, and a further 240 m of earth will absorb the penetrating muon component. An interesting new feature of this neutrino beam is the possible inclusion of a "hadronic hose," which is a current-carrying conductor running along the axis of the decay pipe; the additional focusing provided by this device minimizes any differences in the far and near energy spectra which arise because of geometrical effects. Based on the currently favored oscillation parameters from the Super-Kamiokande experiment (Fukuda et al., 1998;1999), initial running will be in the low energy beam. The beam is mainly ν_μ with only ≈ 0.5% ν_e contamination.

Since the beam must point 58 mrad below the horizontal, extensive tunneling is necessary at Fermilab; the Near Detector will be situated in an enclosure which is 105 m below ground, as indicated in Fig. 2. Given the high intensity of the beam, much consideration has been given to the likely lifetime of components, of the necessary shielding, and of possible radioactive contamination in the local groundwater.

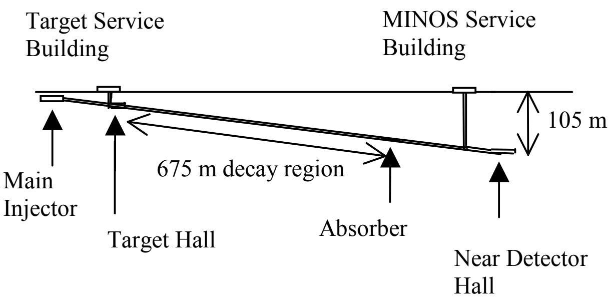

Fig. 2. The beamline at Fermilab

The beam is only about 1 km diameter when it reaches the Soudan site and very accurate alignment of the beam components is necessary. The Global Positioning System (GPS) has been used to survey the beam trajectory which will be known to a precision of about 10 m at Soudan.

At the time of writing (May, 2001), the Fermilab civil construction is well underway. Completion of the beam tunnel and Near Detector hall excavation is imminent and installation of beam line components will begin in July, 2001

3. Soudan site construction

Construction of the new experimental hall at Soudan, adjacent to the existing Soudan-2 hall, began in late 1999 and was completed in Dec., 2000. Outfitting of the space with utilities and the steelwork necessary to accommodate the 5.4-kton Far Detector will be finished in June, 2001 and installation of the detector will begin immediately. The detector consists of two "supermodules," each of which will take 1 year to install, so that complete installation will be accomplished by July, 2002. Fig. 3 shows a sketch of the detector hanging from its considerable support structure. This structure also supports racks containing electronics, photo-detectors, and related equipment. As indicated in the figure, the 8-m wide octagonal steel plates will be assembled underground by welding together two layers of 2-m wide, half-thickness plates that fit down the mineshaft.

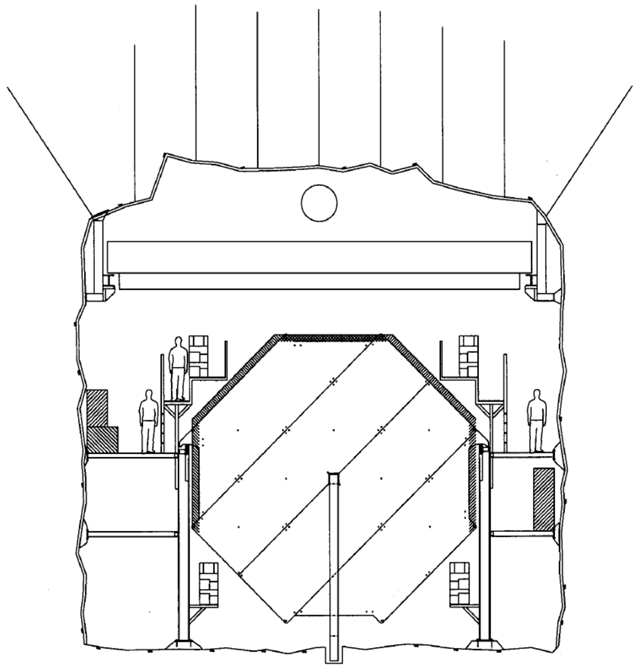

Fig. 3. Front view of a hanging steel plane, showing the support structure and the vertical magnet coil.

4 Manufacture of detector components

4.1 Far Detector

Both Near and Far Detectors have the same general construction: plates of 2.54 cm steel alternating with planes of plastic scintillator. Each scintillator plane is 1 cm thick and is made of 4.1 cm wide strips of scintillator. The orientation of the strips differs by 90° in alternate planes, to provide particle tracking. Each of the two supermodules will contain 242 planes of scintillator. The steel will be magnetized with a field of up to 1.3 Tesla by coils running through each supermodule.

The scintillator is conventional: polystyrene doped with PPO and POPOP fluors, and the strips are co-extruded with an outer reflecting layer of polystyrene containing 15% TiO2 which forms a highly reflective surface. The extruded scintillator contains a 3 mm deep groove into which a 1.2

mm diameter wavelength shifting fiber is glued. The blue scintillation light produced by charged products of the neutrino interactions makes several bounces from the reflective wall, typically, until it hits the fiber where it is absorbed and re-emitted as green light. About 12% of this light is trapped in the fiber, which then acts as a light guide to channel the light along the length of the scintillator strip to pixelated photo-detectors at both ends of the fiber.

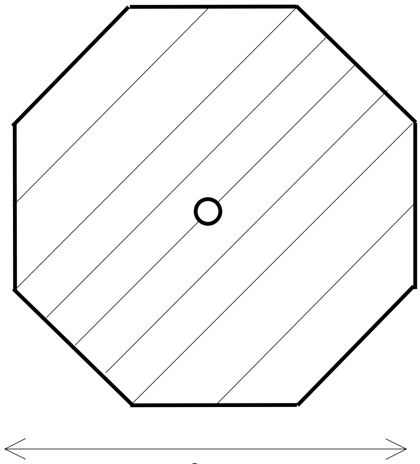

Fig. 4. Layout of scintillator modules on a plane of the Far Detector; there are 4 modules containing 20 scintillator strips and 4 (angled) with 28 strips. The 55 cm diameter central hole accommodates the magnet coil.

For the Far Detector, the scintillator strips are assembled in modules containing 20 and 28 strips each; 4 of each type comprise a single detector plane as shown in Figure 4. These modules incorporate manifolds to guide the fibers to optical connectors at each end and are encased in a 0.5 mm thick sheet of aluminum which is crimped along each edge to make an effective light seal. The modules are being produced in factories at the University of Minnesota and at the California Institute of Technology. Each factory produces 20 to 25 modules per week, on average, more than 125 m^2 of detector, and each will be make almost 2000 modules. As of May, 2001, about 10% of the total Far Detector modules have already been manufactured and shipped to Soudan for immediate installation when beneficial occupancy of the laboratory occurs.

The photo-detectors in the Far Detector are 16-pixel Hamamatsu M16 tubes with 4 mm square pixels. Light from opposite ends of the detector modules is carried to the photo-detectors via clear fiber cables; 8 fibers from strips on the same plane, but separated by at least 1 m, will be connected to each pixel. This multiplexing is necessary to minimize the overall cost of the photo-detectors.

4.2 The Near Detector

The Near Detector is designed to be as similar to the Far Detector as possible; it differs significantly in size, slightly in shape and logically is divided into two separate sections: a target/calorimeter section consisting of 120 planes, and a muon tracking/spectrometer section consisting of 160 planes. Only 1 in 5 planes of the spectrometer section is instrumented. Since the event rates are high (potentially several/pulse) in the Near Detector, and there is a significant possibility of event overlap, multiplexing of the signals will not be used. The photo-detectors will be 64-pixel Hamamatsu M-64 tubes.

The Near Detector modules are being manufactured at Argonne National Laboratory; these comprise about 10% of the area of the Far Detector scintillator.

4.3 Module mapping/quality control

An important feature of the quality control process is the mapping of each module immediately after manufacture. Modules are placed on a table and a 3 mCurie ^{137}Cs γ-ray source is programmed to travel transversely across each module at intervals of 4 cm. The resulting dc current in each strip is measured with a precision of about 1% and the results fed into a database for future reference. An example of the output from a single strip is shown in Fig. 5. The two lower curves are proportional to the dc current read out from opposite sides of the strip and show the typical attenuation of light along the length of the wavelength-shifting fiber (caused primarily by self-absorption in the fiber). These two curves are fitted to a double exponential and the ratio of the data to the fits is shown in the upper two curves which are essentially superimposed, indicating the precision of the procedure. The overall normalization to photoelectron yield at the photo-detector is accomplished by comparison with separate cosmic ray runs using reference detector modules: the summed pulse heights give a yield of 12 photoelectrons, typically. Each module is mapped again after it arrives underground at Soudan, to ensure that damage has not occurred during shipping.

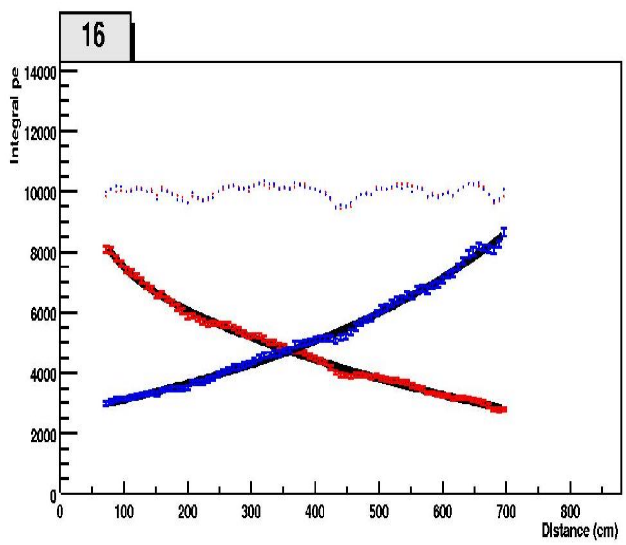

Fig. 5. Response map of strip 16 in a typical 8-m long scintillator module.

5 Calibration

A small calibration detector, 1 m square, and comprised of 60 planes with the same steel/scintillator configuration as the main detectors has been constructed. It is being used to investigate detector response to beams of hadrons, muons, and electrons in a test beam at CERN. The overall relative calibration between the Near and Far Detectors will actually be determined using cosmic ray muons.

Any non-linearity in the readout, or changes in short-term response of the photo-detectors will be tracked using an extensive light pulsing scheme that injects light from blue LEDs into all fibers, inside the detector modules.

6 Physics capabilities of MINOS

The MINOS experiment will be the first accelerator experiment to study neutrino oscillations with high precision. Fig. 6 shows the number of charged current (CC) events expected within two years for the three possible neutrino beams; the numbers vary from about 1,500 to 30,000 for the low-energy and high-energy configurations, respectively.

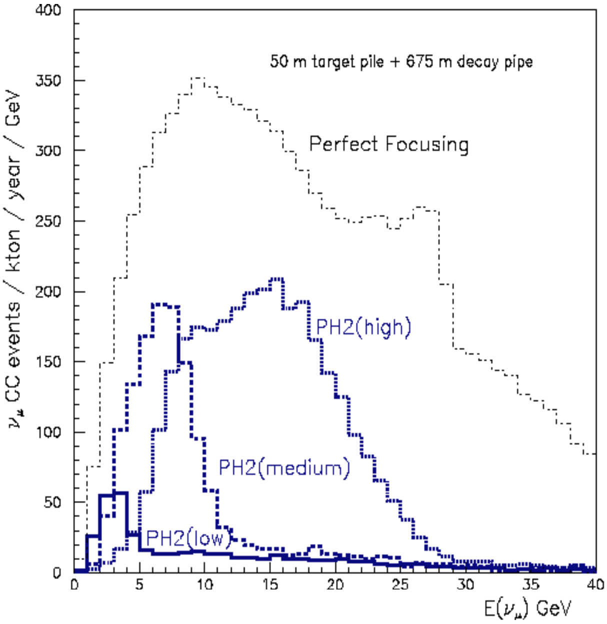

Fig. 6. CC event rates for the 3 possible beams; "perfect focusing" refers to the idealized situation where all produced mesons are focused down the beamline without loss.

The latest results from the SuperKamiokande experiment favor Δm^2 values in the region 3-5×10^{-3} eV^2 for ν_μ - ν_τ mixing. The probability for oscillation from one flavor to another is proportional to the well-known function

$$\sin^2(2\theta).\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

where $sin^2(2\theta)$ is the so-called "mixing" parameter and the units of distance L and energy E are km and GeV, respectively. For the favored Δm^2, the maximum transition probability occurs in the region 2 – 3 GeV and we have chosen the low-energy beam to begin the experiment.

The most straightforward measurement to be made is the disappearance of ν_μ from the beam. This will be done by measuring the ratio of "long" events in which a ν_μ interacts via a CC interaction and producing a penetrating muon, to "short" events which contain neutral current (NC) interactions of the ν_μ, or CC events of either ν_τ or ν_e. By comparing this ratio in Far and Near Detectors, most systematic errors cancel.

A more satisfying measurement will be the direct observation of ν_μ oscillations by comparison of the ν_μ CC energy spectra in both detectors. Observation of the oscillation structure will permit us to measure the values of both oscillation parameters, $\Delta m^2$and $sin^2 2\theta$ with a precision ~5-10%. In order to be successful, we need to understand the relative energy calibration between the two detectors to approximately 2%.

There are many other measurements possible in MINOS; in particular, the appearance of ν_e or ν_τ at the Far Detector, following oscillation from the initial ν_μ beam would provide a convincing demonstration of the oscillation phenomenon. Statistical fluctuations in the initial beam flux will limit the sensitivity to ν_μ - ν_e oscillations to about 2×10^{-3} in the mixing angle. Use of the low-energy beam precludes direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations since the neutrinos have too low an energy to produce taus directly, but studies have shown that in either the medium- or high-energy beams, the presence of a small number of taus could be inferred.

7 Conclusion

The MINOS experiment will provide an opportunity to measure neutrino oscillation parameters to a high precision in a controlled accelerator experiment. The large-scale construction necessary to carry out the project is well underway: a Far Detector Laboratory has already been excavated and installation of the Detector will be completed in mid-2003. Construction of the beam at Fermilab, and of the smaller Near Detector will also be complete at that time.

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References

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