Status of the MINOS experiment

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The MINOS long-baseline neutrino oscillation experiment is presently under construction at the Soudan mine and the Fermi National Accelerator Laboratory. We report on the current status of the experiment, the projected schedule and its physics capabilities.

1. Introduction

Growing evidence for neutrino oscillations being responsible for the observed solar and atmospheric neutrino anomalies [1,2] has shown the necessity of second generation experiments using a well-controlled and understood neutrino source. The MINOS (Main Injector Neutrino Oscillation Search) experiment [3] is a long baseline neutrino oscillation experiment utilizing a neutrino beam produced at FNAL and directed at a 5.4 kt detector (Far Detector) located 731 km away in the Soudan mine, northern Minnesota. A smaller 980-ton detector (Near Detector) will measure the neutrino beam at the Fermilab site where no effect from neutrino mixing is expected. Comparison between the two detectors will allow the measurement of the oscillation parameters with a high accuracy providing their true values are within the region indicated by Super-Kamiokande [4].

2. Neutrino beam

The Main Injector is a high intensity proton synchrotron which has a multiple purpose of producing the antiprotons for the Tevatron, preaccelerating protons and antiprotons before their injection into the Tevatron and providing an intense beam for fixed target experiments. The NuMI (Neutrinos at Main Injector) neutrino beam is obtained from the decay of pions and kaons produced in the interactions of 120 GeV protons with a carbon target. The anticipated proton flux is 4×10^{13} protons per pulse with a repetition rate of 1.9 sec. Single turn extraction will be used with a pulse length of 10 μs.

The secondary mesons will be focused by two parabolic horns and allowed to decay in a 675 m long evacuated decay pipe. Combining this with the 50 m distance from target to start of the decay pipe gives a 725 m long decay region for the beamline. The distance between the two horns can be changed by moving the second horn with respect to the other. By adjusting the horn positions and currents one can select three different neutrino energy regimes: low ($< E_\nu >\sim 3GeV$), medium ($< E_\nu >\sim 6GeV$) and high ($< E_\nu >\sim 15GeV$). The anticipated neutrino event spectra at the far detector site for the three energy configurations are shown in Fig. 1. The possibility to optimize the beam energy during the course of the experiment provides the flexibility to react to the initial results. In order to have optimal sensitivity in the low part of the atmospheric neutrino allowed region preferred by Super-Kamiokande data [4] the collaboration have decided to start taking data with the low-energy beam configuration. Two years of data taking in this configuration would yield about 5,000 beam-related charge-current (CC) neutrino events in the Far Detector in the absence of oscillations. The statistics would be much higher in the high-energy beam configuration: about 30,000 ν_μ CC events are expected in this case.

An alternative method of changing the beam energy is currently being investigated. It is proposed to implement a flexible arrangement where the target can be remotely moved in the beamline direction to change the beam energy and the horns remain fixed [5]. In addition to having the possibility of a continuously-variable beam energy, the movement of the target can be performed more quickly, thus reducing the downtime significantly.

Substantial progress has been made in the NuMI beamline construction. The excavation of the proton carrier tunnel and target hall are completed. Most of the decay tunnel and some portion of the Near Detector hall are also excavated. The NuMI beam turn on is expected in autumn 2004.

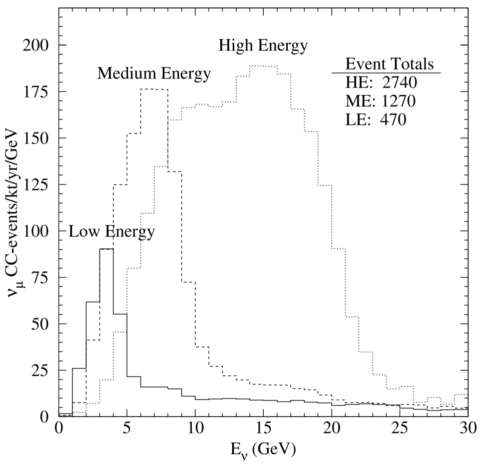

Figure 1. Neutrino interaction spectra in the far detector predicted for three different focusing conditions corresponding to high, medium and low energy beam.

3. MINOS Detectors

MINOS design includes two detectors: the Far Detector and the Near Detector. One can obtain an unbiased pattern of oscillations comparing the Near/Far neutrino rates and energy spectra . The detectors have been designed to be as similar as possible. They are iron/scintillator sampling calorimeters with identical longitudinal and transverse granularity and an average toroidal magnetic field of about 1.3 T. The 2.54 cm thick iron plates are interleaved with scintillator planes composed of 4.1 cm wide, 1.0 cm thick strips. The strip orientation differs by 90 degrees in successive planes so as to provide X and Y coordinate measurements, Z being the number of the plane. The scintillator is commercially extruded polystyrene. A thin TiO_2 loaded layer has been coextruded on the outside to provide a reflective surface layer and a protective layer for handling. Each strip has a groove about 2 mm deep and 1.3 mm wide located in the centre of one wide side. A green wavelength-shifting fiber, 1.2 mm in diameter, is glued into the groove. The light produced in the scintillator is trapped into the fiber, shifted in frequency and delivered to the photomultipliers. Although the principal design of both detectors is very similar there are differences reflecting the fact that experimental conditions at the near and far site are not identical.

3.1. Far Detector

The MINOS Far Detector will be located in a newly excavated cavern in the Soudan mine 690 m below the surface. The detector is composed of 486 iron/scintillator octagonal modules giving a total mass of 5.4 kt. The detector will be split up into two independent supermodules, each one toroidally magnetized by a current carrying coil threaded through a hole through the center of the super-module. A sketch of one supermodule is shown in Fig. 2. The scintillator strips in the Far Detector are read out from both ends. Clear fibers are used to transport the light from the green fibers to 16 pixel Hamamatsu M16 photomultiplier tubes. Each pixel is 4×4 mm^2 and will be coupled to 8 fibers from 8 different scintillator strips from the same plane but spaced about 1 m apart. Such multiplexing provides a substantial reduction in cost of photomultipliers and readout electronics. The set of strips connected to a given pixel is different at the two ends allowing one to "de-multiplex" the event using the resulting pattern difference, i. e. to identify which strips were responsible for a particular event.

A detailed GEANT-based Monte-Carlo simulation of the MINOS detector gives an energy resolution σ/E of approximately $23\%/\sqrt{E}$ for elec-

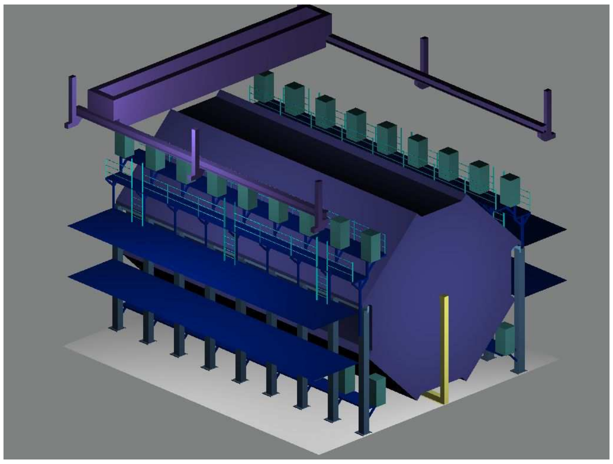

Figure 2. Sketch of the MINOS Far Detector supermodule

tromagnetic showers and $55\%/\sqrt{E}$ for hadronic showers. The magnetic field allows measurement of the muon momentum by curvature (14% resolution for a 10 GeV muon) as well as by range for stopping muons ($\sim 6\%$).

Civil construction and outfitting of the Soudan mine is complete and the detector installation has begun. At the time of writing 100 planes have been installed and commissioned which is $\sim 41\%$ of the first supermodule (~ 1.1 kt). Routine installation of the Far Detector continues at a rate of 5–7 planes/week, faster that it was anticipated in the original schedule. First cosmic ray muons have been already observed in the installed planes which are also used to debug calibration and DAQ procedures. The installation of the first supermodule will be completed by September 2002. During the construction of the second supermodule the first supermodule will be used to acquire the cosmic ray and atmospheric neutrino data. The whole detector installation will be completed by September 2003.

MINOS will be the first large underground neutrino experiment using a magnetic field and atmospheric neutrino and upward going muons studies can greatly benefit from that. Even though the statistical significance will be below that of Super-Kamiokande, MINOS will be able to measure the charge of the muons as well as the energy of throughgoing and partially contained events.

3.2. Near Detector

The Near Detector is functionally identical to the Far Detector although its physical design has some different features due to the differences in characteristics of the neutrino beam at the two sites such as, for instance, much higher rates and a slightly lower average energy of the neutrino beam at the near site compared to the far site due to the effect of beam divergence. The detector has the same composition and modularity as the Far Detector and is composed of 282 “squashed” octagon plates giving a mass of 980 t. The detector is divided into two parts: 120-plane calorimeter consisting of “veto”, “target” and “hadron spectrometer” regions and 162-plane muon spectrometer (Fig. 3). In the calorimeter section 4/5 of the plates are partially instrumented around the beam fiducial region; every fifth plane is fully instrumented. The planes in the muon spectrometer section are fully instrumented but only every fifth plane. One sided optical readout with no optical summing will be used. The fibers will be read out by Hamamatsu M64 tubes (64 2×2 mm^2 pixels). The average magnetic field seen by a muon will be practically identical in both Near and Far Detectors. The Near Detector will be used to study carefully the beam, to measure ν_e contamination and to understand the beam at the far detector site which will substantially reduce the systematic uncertainty of the prediction. Excavation of the Near Detector hall is underway. About half of the steel required for the Near Detector has been delivered. Installation of the detector is expected to start in October 2003 and will take about 8 months.

4. Calibration

The two MINOS detectors must have a relative energy calibration of 2% in order to reduce systematic errors to less than the expected statistical errors on the oscillation parameters. This will be accomplished in several stages. Any non-

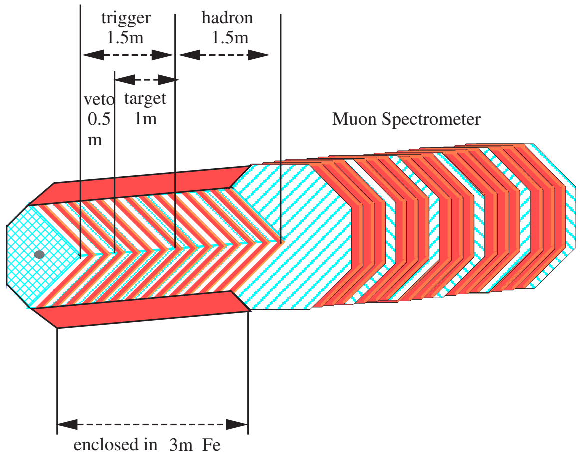

Figure 3. Sketch of the MINOS Near Detector

linearity in the readout as well as any short-term changes in PMT gain will be measured by injecting light from pulsed LEDs into the readout chain [6]. Cosmic ray muons will be used to perform the strip-to-strip calibration and the relative calibration between the Near and Far Detectors. Finally, a comparison of the energy deposition by muons with that from electromagnetic and hadronic showers will be carried out with a smaller detector (the Calibration Detector) which is a replica of the MINOS detectors but with a more manageable size. The Calibration Detector was built, commissioned and exposed in 2001 to the T11 test beam at CERN with far detector readout electronics. The analysis of this data is currently underway. The calibration program for the next three years includes the exposure of the detector equipped with far and near detector electronics to hadrons, electrons and muons of known energies at the T7, T9 and T11 testbeam areas at CERN [7].

5. Physics Goals and Sensitivity

Large statistics and well controlled systematics give MINOS powerful physics tools to study neutrino oscillation phenomena. The experiment will address the following issues:

- The neutrino oscillation hypothesis with $\nu_\mu \rightarrow \nu_\tau$ being the dominant mode. In this case MINOS should see the disappearance in the ν_μ charge current (CC) sample without loss of neutral current (NC) events and without appearance in the ν_e CC sample.
- Precise measurement (at the roughly 10% level) of the oscillation parameters Δm^2 and $sin^2 2\theta$ for the dominant $\nu_\mu \rightarrow \nu_\tau$ mode. The primary measurement for this is the comparison of rates and spectra of the CC events in the Far and Near Detectors.
- Measurement or improvement of the limit on the $\nu_\mu \rightarrow \nu_{sterile}$ oscillation mode. This can be done by comparing NC/CC ratio with what is predicted for the $\nu_\mu \rightarrow \nu_\tau$ oscillation mode.
- Measurement or improvement of the limit on the $\nu_\mu \rightarrow \nu_e$ oscillation mode. The ν_e CC appearance can be detected using topological criteria for electromagnetic shower identification.
- Studying possible contributions from more exotic hypotheses such as neutrino decay [8], extra dimensions [9] or decoherence [10].

Below we shall elaborate on some of these studies in more detail and estimate potential sensitivities that could be achieved in a 10 kt-yr run which corresponds to a run of approximately 2 years' duration.

$\underline{\nu_\mu \rightarrow \nu_\tau}$. The most robust oscillation measurement MINOS will offer is a determination of any change in the ratio of the numbers of NC versus CC events between the Near and Far Detectors – $\frac{(NC/CC)_{near}}{(NC/CC)_{far}}$. This test is relatively systematic free as the expected NC/CC ratio in the absence of oscillations is fairly constant over the entire range of neutrino energies. The uncertainties due to Monte Carlo based acceptance and absolute neutrino flux calculations essentially cancel, thus reducing systematics significantly. A simple and robust mechanism to discriminate between NC and CC ν_μ events is a cut based on event length. More sophisticated methods including pattern recognition of the muon track and artificial neural networks to identify event types are being studied.

The recent Super-Kamiokande results from 1289 days of contained events and up-going muon events give 90% C.L. allowed parameter regions of $sin^2 2\theta > 0.88$ and $1.6 \times 10^{-3} < \Delta m^2 < 4.0 \times 10^{-3} eV^2$ [4]. According to the results of the search for charged current ν_τ events, the Super-K data is consistent with ν_τ appearance at roughly the two sigma level. This led the MINOS collaboration to the decision to use the low energy beam configuration for the initial run.

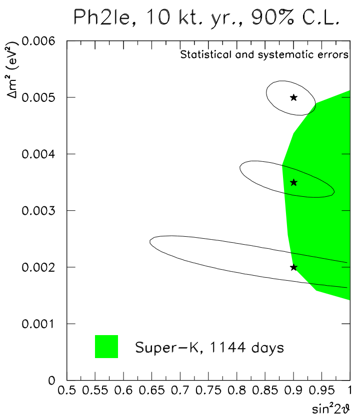

Figure 4. Expected Δm^2 and $sin^2 2\theta$ sensitivity for a 10 kt-yr exposure with the low energy beam. The Super-K 90% allowed region is also shown, shaded

Neutrino oscillations will deplete the ν_μ flux at certain energies. A measurement of the ν_μ energy spectrum will therefore yield the mixing parameters directly. Fig.4 shows the sensitivity of the CC energy test to the oscillation mixing parameters for three different Δm^2 values: 0.002, 0.0035 and 0.005 eV^2. The parameter region allowed by Super-K data is also shown. In the absence of oscillations the measurement of the ν_μ CC spectrum will provide the most stringent limit on Δm^2 of $< 7 \times 10^{-4} eV^2$ at the maximum mixing angle at 90% C.L. as shown in Fig. 5. Both plots assume a 10kt-yr exposure and the low energy beam option.

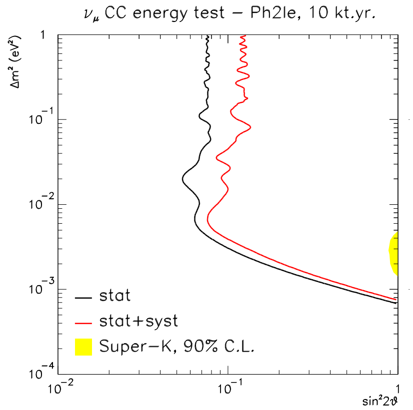

Figure 5. Expected 90% confidence limits from the CC energy distributions in MINOS for a 10 kt-yr exposure with the low energy beam. The Super-K 90% allowed region is also shown, shaded

$\nu_\mu \rightarrow \nu_{sterile}$. Although the Super-Kamiokande analysis shows that pure $\nu_\mu \rightarrow \nu_{sterile}$ oscillation is disfavoured at 99% C.L. MINOS can improve current limits with the NC/CC ratio measurement. In [11] it was shown that more stringent limits can be obtained for three different oscillation scenarios: $\nu_\mu \rightarrow \nu_\tau$, 50% $\nu_\mu \rightarrow \nu_\tau$ + 50% $\nu_\mu \rightarrow \nu_{sterile}$ and $\nu_\mu \rightarrow \nu_{sterile}$.

$\nu_\mu \rightarrow \nu_e$. ν_e interactions can be identified by the presence of an electromagnetic shower. The MINOS tracking calorimeters should be able to identify such a shower using its typical characteristics such as shower compactness in both longitudinal and transverse dimensions and a large deposit of energy near the vertex. One background is the ν_e component in the beam ($\sim 0.6\%$). A somewhat more serious background is generated by the NC events with a topology similar to a ν_e interaction. Both these backgrounds can be measured with the Near Detector and the corresponding uncertainty will be mainly due to statistical fluctuations in their predicted number in the Far Detector. The simulations show that MINOS can offer a modest improvement over the best current limit by CHOOZ [12] (Fig. 6).

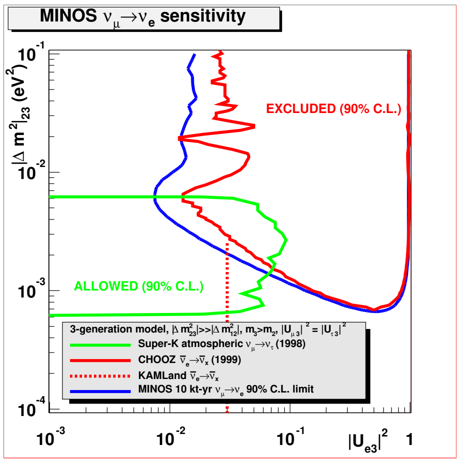

Figure 6. MINOS $\nu_\mu \to \nu_e$ sensitivity for a 10 kt-yr exposure. The region excluded by CHOOZ and predicted KamLAND limit are also shown

Should the rate be measurable, MINOS would be able, thanks to the magnetic field, to measure the sign of Δm^2 by performing the same measurement with $\bar{\nu}_\mu$ using the fact that matter effects contribute with opposite sign for a neutrino and an antineutrino beam.

6. Conclusion

Large scale construction of the MINOS experiment is underway. The installation and commissioning of the detectors in the Soudan mine and FNAL will be completed by summer 2004. We expect the beam to turn on in late 2004. In two years of data taking MINOS will be able not only to confirm the oscillation hypothesis but to provide also the first ever high precision measurement of the neutrino mixing parameters.

Acknowledgements

Funding for MINOS has been provided by the U.S. Department of Energy and by the U.K. Particle Physics and Astronomy Research Council.

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