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Search for Muon-Neutrino to Electron-Neutrino Transitions in MINOS


1Argonne National Laboratory, Argonne, Illinois 60439, USA
2Department of Physics, University of Athens, GR-15771 Athens, Greece
3Physics Department, Benedictine University, Lisle, Illinois 60532, USA
4Brookhaven National Laboratory, Upton, New York 11973, USA
5Lauritsen Laboratory, California Institute of Technology, Pasadena, California 91125, USA
6Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom
7Universidad Estadual de Campinas, IFGW-UNICAMP, CP 6165, 13083-970, Campinas, SP, Brazil
8APC-Université Paris 7 Denis Diderot, 10, rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France
9Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
10Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
11Holy Cross College, Notre Dame, Indiana 46556, USA
12Physics Division, Illinois Institute of Technology, Chicago, Illinois 60616, USA
13Indiana University, Bloomington, Indiana 47405, USA
14Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
15Nuclear Physics Department, Lebedev Physical Institute, Leninsky Prospect 53, 119991 Moscow, Russia
16Lawrence Livermore National Laboratory, Livermore, California 94550, USA
17Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom
18University of Minnesota, Minneapolis, Minnesota 55455, USA
19Department of Physics, University of Minnesota-Duluth, Duluth, Minnesota 55812, USA
20Otterbein College, Westerville, Ohio 43081, USA
21Subdepartment of Particle Physics, University of Oxford, Oxford OX1 3RH, United Kingdom
22Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
23Rutherford Appleton Laboratory, Science and Technology Facilities Council, OX11 0QX, United Kingdom
24Instituto de Física, Universidade de São Paulo, CP 66318, 05315-970, São Paulo, SP, Brazil
25Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208, USA
26Department of Physics, Stanford University, Stanford, California 94305, USA
27Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
28Physics Department, Texas A&M University, College Station, Texas 77843, USA
29Department of Physics, University of Texas at Austin, 1 University Station C1600, Austin, Texas 78712, USA
30Electron Neutrino to Muon Neutrino oscillation search at MINOS
Several experiments have provided compelling evidence for muon-neutrino disappearance as a function of neutrino energy and distance traveled [1–7]. These observations support the description of neutrinos in two distinct mass and flavor bases, related by the $3 \times 3$ neutrino mixing matrix [8]. The MINOS experiment provides the most precise measurement of the atmospheric mass splitting, $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV$^2$ [7,9]. At this mass scale, the dominant oscillation channel is expected to be $\nu_\mu \rightarrow \nu_\tau$, but subdominant $\nu_\mu \rightarrow \nu_e$ transitions are not excluded [10]. Observation of $\nu_e$ appearance would imply a nonzero value of $\theta_{13}$, opening the possibility of observing CP violation in the leptonic sector. The current best experimental limit [11], implies $\sin^2(2\theta_{13}) < 0.15$ at the 90% confidence level (C.L.) for the MINOS $|\Delta m^2|$ value. However, recent global analysis of several neutrino experiments suggests a nonzero value of $\theta_{13}$ [12]. In addition to these parameters, the probability of electron-neutrino transitions in MINOS depends on $\sin^2(\theta_{23})$, the CP violation parameter, $\delta_{CP}$, and the sign of $\Delta m^2$. Two other experiments have given limits with less sensitivity [13,14]; MINOS is the first experiment to probe $\sin^2(2\theta_{13})$ with sensitivity comparable to the CHOOZ limit at $|\Delta m^2| = 2.43 \times 10^{-3}$ eV$^2$ and $\sin^2(2\theta_{23}) = 1.0$.

Neutrino interactions from a beam produced by the Fermilab NuMI facility [15] are recorded at the MINOS Near (ND) and Far (FD) Detectors, located at 1 km and 735 km, respectively, from the production target. High statistics data from the ND establish the properties of the beam before oscillations. Observation of additional $\nu_e$ interactions in the FD relative to the ND provides evidence of $\nu_\mu \rightarrow \nu_e$ oscillation. The two detectors are of similar design to reduce systematic uncertainties from the physics of neutrino interactions, the neutrino flux, and detector response [7,16,17]. The detectors are magnetized, tracking calorimeters composed of planes each with layers of 2.54 cm thick steel and 1.0 cm thick scintillator (1.4 radiation lengths per plane). The scintillator layer is composed of 4.1 cm wide strips (1.1 Molière radii).

The beam is comprised of 98.7% $\nu_\mu + \bar{\nu}_\mu$ and 1.3% $\nu_e + \bar{\nu}_e$. The latter originate from decays of muons produced in pion decays and from kaon decays. The $\nu_e$ flux below 8 GeV is largely from muon decay and is well constrained by the measured $\nu_\mu$ flux [7,18]. The present analysis is based on an integrated exposure of $3.14 \times 10^{20}$ protons delivered to the NuMI target.

The search for electron-neutrino appearance relies on identifying charged current (CC) $\nu_e + Fe \rightarrow e + X$ interactions that produce an energetic electron [19]. This electron initiates an electromagnetic cascade and deposits its energy in a relatively narrow and short region in the MINOS calorimeter. Additional calorimeter activity is produced by the breakup of the recoil nucleus ($X$). Other neutrino scattering processes can produce similar event topologies in the MINOS detector. These include neutral current (NC) $\nu + Fe \rightarrow \nu + X$ interactions and $\nu_\mu$-CC interactions with low-energy muons, both having hadronic showers with an electromagnetic component arising from $\pi^0$ decays. Less significant backgrounds arise from intrinsic beam $\nu_e$-CC interactions, $\nu_\mu$-CC interactions from oscillations, and cosmogenic backgrounds.

We select events with reconstructed energy between 1 and 8 GeV, encompassing the maximum of the $\nu_\mu \rightarrow \nu_e$ oscillation probability. The lower limit mainly removes NC events, while the higher limit removes beam $\nu_\mu$-CC events from kaon decays. Additionally, events are selected to be in time with the accelerator beam pulse, and directional requirements are applied to limit background from cosmogenic sources to less than 0.5 events (90% C.L.). Events are required to have a reconstructed shower and at least 5 contiguous planes each with energy deposition above 1 MeV. Events with tracks longer than 25 planes are rejected. Monte Carlo (MC) simulations indicate that these cuts improve the signal-to-background ratio from 1:55 to 1:12, assuming $\sin^2(2\theta_{13}) = 0.15$.

Further enrichment of the $\nu_e$-CC selected sample is achieved using a method based on an artificial neural network (ANN) with 11 input variables characterizing the longitudinal and transverse energy deposition in the calorimeter that separate the signal $\nu_e$-CC events from NC and $\nu_\mu$-CC background [20]. The acceptance threshold is determined by maximizing the ratio of the accepted signal to background.
the expected statistical and systematic uncertainty of the background. With these selection criteria, and assuming $\sin^2(2\theta_{13}) = 0.15$, this method gives a 1:4 signal-to-background ratio.

The Monte Carlo simulation of the beam line and detectors is based on GEANT3 [21] and the hadron production yields from the target are calculated by FLUKA [22]. The calculated neutrino flux is adjusted to agree with the ND $\nu_\mu$-CC data [18]. Neutrino interactions and further reinteractions of the resulting hadrons within the nucleus are simulated with NEUGEN3 [23]. Uncertainties in the composition and kinematic distribution of the particles that emerge from the nucleus can be large, but these and many other uncertainties mostly cancel when comparing neutrino interactions between the ND and FD.

Events selected by the ANN in the ND predict the number of background events expected in the FD and reduce reliance on the simulation. Considerations of oscillations and beam line geometry require that each background component, $\nu_\mu$-CC, NC, and beam $\nu_e$-CC, be treated separately in the prediction of the FD backgrounds. The first two background components are determined using an NC-enriched data sample recorded with the NuMI magnetic horns turned off. In this configuration the pions are not focused; the low-energy peak of the neutrino energy distribution disappears, leaving an event sample dominated by NC events from higher energy neutrino interactions. These data are used in conjunction with the standard beam configuration data, and the simulated ratios of the horn-on to horn-off rates for each component, to extract the individual NC and $\nu_\mu$-CC background spectra. The smaller beam $\nu_e$-CC component is calculated from the MC simulations using $\nu_\mu$-CC events observed in the ND.

Figure 1 shows the data in the ND and the derived NC, $\nu_\mu$-CC, and beam $\nu_e$-CC backgrounds. The ND background is $(57 \pm 5)\%$ NC, $(32 \pm 7)\%$ $\nu_\mu$-CC and $(11 \pm 3)\%$ beam $\nu_e$-CC events. Systematic errors on the components arise from uncertainties in the beam flux, cross section and selection efficiency. The errors on the NC and $\nu_\mu$-CC components are derived from the data and are correlated due to the constraint that the background must add to the observed ND event rate. The uncertainty on the beam $\nu_e$-CC comes from the $\nu_\mu$-CC events observed in the ND [18].

As a crosscheck, a second technique to study the ND background sample uses an independent sample of showers from $\nu_\mu$-CC events selected with long tracks [7]. The hits associated with the muon track are removed from the event, and the remainder showers are subsequently analyzed as a sample of NC-like events [24,25]. The procedure is applied to the data and MC calculations, and the $\nu_e$-CC selections are applied to both. Differences between the muon-removed data and muon-removed MC samples are used to adjust the predicted NC background. As in the first method, the beam $\nu_e$-CC background is taken from the MC samples, and the remainder of the observed ND background are classified as $\nu_\mu$-CC events. The background components calculated from the muon-removed sample agree with those obtained from the horn-off method [26].

After decomposition of the ND energy spectrum into background components, each of these spectra is multiplied by the Far to Near energy spectrum ratio from the simulation for that component, providing a prediction of the FD spectrum. The simulation takes into account differences in the spectrum of events at the ND and FD due to beam line geometry as well as possible differences in detector calibrations and event shape. Oscillations are included when predicting the $\nu_\mu$-CC component. We expect 26.6 background events, of which 18.2 are NC, 5.1 are $\nu_\mu$-CC, 2.2 are beam $\nu_e$ and 1.1 are $\nu_\tau$ [27].

To estimate the efficiency for selecting $\nu_e$-CC events, we use the muon-removed events from data and MC calculations, then embed a simulated electron of the same momentum as the removed muon. Test beam measurements [28] indicate that the selection efficiency of single electrons agrees with the simulation to within 2.6%. The $\nu_e$-CC selection efficiency obtained from the data agrees with the selection efficiency obtained from the MC calculations to within 0.3%. We estimate our efficiency for selecting $\nu_e$-CC events to be $(41.4 \pm 1.5)\%$ [25].

Systematic uncertainties are evaluated by generating modified MC samples and by quantifying the change in the number of predicted background events in the FD. Table 1 shows that the dominant uncertainties arise from far-near differences: relative energy scale calibration dif-
fers (a), details of the modeling of the photomultiplier tube (PMT) gains (b) and crosstalk (c), and relative event rate normalization (d). Other uncertainties resulting from neutrino interaction physics, shower hadronization, intranuclear rescattering, and absolute energy scale uncertainties (e) affect the events in both detectors in a similar manner and mostly cancel in the extrapolation. The individual systematic uncertainties are added in quadrature along with the uncertainty arising from the background decomposition in the ND to give an overall systematic uncertainty of 7.3% on the expected number of background events selected in the FD. The expected statistical uncertainty is 19%.

The prediction and uncertainty of the backgrounds in the FD are established before examining the FD data. Additionally, the independent and signal-free muon-removed FD data sample is examined. In that sample, we observe 39 events, with an expectation of 29 ± (stat) ± 2(syst). The selected events were investigated and no evidence of abnormalities was found.

Figure 2 shows the FD data as a function of the ANN selection variable. The signal acceptance threshold was optimized prior to examination of the FD data to be 0.7. We observe 35 events in the signal region with a background expectation of 27 ± 5(stat) ± 2(syst). In the region of the selection variable well below the acceptance threshold (<0.55), we observe 146 events, compared to a pure background expectation of 132 ± 12(stat) ± 8(syst). The observed energy spectrum for the events in the signal region is shown in Fig. 3.

A second selection method, Library Event Matching, is used as a crosscheck. In this technique, each candidate is compared to a large library of simulated νe-CC and NC events [29]. This method gives a better background rejection than the ANN algorithm, but with increased sensitivity to some uncertainties. As in the ANN method, we observe a small excess (<2σ) for the muon-removed sample and in the region below the selection cut. In the signal region, we observe 28 selected events, with a background expectation of 22 ± (stat) ± 3(syst); these results are consistent with the ANN selection.

Figure 4 shows the values of sin²(2θ13) and δCP that give an excess of events consistent with our observation from the ANN selection. The oscillation probability is computed using a full 3-flavor neutrino mixing framework that includes matter effects [30], which introduces a dependence on the neutrino mass hierarchy (the sign of Δm²). The MINOS best fit values of |Δm²| = 2.43 × 10⁻³ eV² and sin²(2θ13) = 1.0 are used as constants in the calculation.
Statistical fluctuations (Poisson) and systematic effects (Gaussian) are incorporated via the Feldman-Cousins approach [31] which determines the confidence intervals.

In conclusion, we report the first results of a search for $\nu_e$ appearance by the MINOS experiment. The 35 events in the Far Detector after $\nu_e$ selection for $3.14 \times 10^{20}$ protons-on-target are $1.5\sigma$ higher than the background expectation of $27 \pm 5\text{(stat)} \pm 2\text{(syst)}$. Assuming $|\Delta m^2_23| = 2.43 \times 10^{-3}$ eV$^2$ and $\sin^2(2\theta_{23}) = 1.0$, the best fit for the normal hierarchy is just below the CHOOZ [11] limit for all values of $\delta_{CP}$.

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*Deceased

[9] The experiment measures an unresolved mixture of $|\Delta m^2_{12}|$ and $|\Delta m^2_{32}|$ which we refer to as $|\Delta m^2|$, for brevity. For further discussion see G. Fogli et al., Prog. Part. Nucl. Phys. 57, 742 (2006).
[19] The experiment does not distinguish $\nu_\mu$ and $\bar{\nu}_\mu$; the dominant contribution is expected from $\nu_\mu \rightarrow \nu_e$ oscillations.
[27] Using $\Delta m^2_{32} = 2.43 \times 10^{-3}$ eV$^2$, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0$.
[30] E. K. Akhmedov et al., J. High Energy Phys. 04 (2004) 078. Eq. 2.1 was used with constant density = 2.75 g/cm$^3$, $\Delta m^2_{21} = 8.0 \times 10^{-5}$ eV$^2$ and $\alpha = \Delta m^2_{21}/\Delta m^2_{32} \approx 0.033$.