Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam

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This letter reports new results from the MINOS experiment based on a two-year exposure to muon neutrinos from the Fermilab NuMI beam. Our data are consistent with quantum mechanical oscillations of neutrino flavor with mass splitting $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2$ (68\% confidence level) and mixing angle $\sin^2(\theta) > 0.90$ (90\% confidence level). Our data disfavor two alternative explanations for the disappearance of neutrinos in flight, namely neutrino decays into lighter particles and quantum decoherence of neutrinos, at the 3.7 and 5.7 standard deviation levels, respectively.

Several experiments have produced compelling evidence of the disappearance of neutrinos of a given lepton flavor. In previous publications, the MINOS experiment has also presented evidence for energy-dependent disappearance of muon neutrinos produced by the NuMI facility at Fermilab. Based on the number of events, that result provides evidence of the disappearance of $\nu_\mu$ at a level of 5.2 standard deviations. Such observations support the description of neutrinos via two independent bases, the mass and the flavor eigenstates, with the bases related by the $3 \times 3$ PMNS matrix. They imply that at least two of the neutrino eigenstates have non-zero mass. In this letter we present results obtained from a larger dataset than that used in previous analysis, the Monte Carlo simulation and the Run I and Run II data sets are analyzed separately to account for this shift.

The simulation of neutrino production and detection is accomplished with a model of hadron production in the target using FLUKA and a GEANT3 simulation of the beamline and detector. NEUGEN3.5.5, tuned to data from previous bubble chamber neutrino experiments and experiments with pion beams scattering on iron, is used to model neutrino interactions. As in our previous analysis, the Monte Carlo (MC) simulation of the neutrino flux was constrained to agree with the neutrino energy spectrum in the ND collected in nine different configurations of the NuMI beam, thereby reducing uncertainties in the flux prediction at the FD. Fig. compares the simulation to the ND data acquired in the two configurations used in the oscillation analysis.

Neutrino interactions in the MINOS detectors can either be charged-current, $\nu_\mu + \text{Fe} \rightarrow \mu^- + X$, or neutral-current, $\nu_\mu + \text{Fe} \rightarrow \nu_\mu + X$. In this analysis, only the former are used because they identify the interacting neutrino flavor and because the reconstructed energy best measures the full neutrino energy. To select charged-current events, we have implemented a new algorithm based on a multivariate likelihood including four variables that characterize a muon track: the event length; the average pulse height per plane along the track; the transverse energy deposition profile of the track; and the fluctuation of the energy deposited in scintillator strips along the track. The new selection algorithm, along with a new track-finding algorithm, improve our efficiency to identify and select charged-current interactions in the FD from 75.3\% using the previous selection to 81.5\% in the current selection, in the absence of oscillations. The new selection reduces the neutral-current contamination in the charged-current sample from 1.8\% in our previous

PACS numbers: 14.60.Lm, 14.60.Pq, 29.27.-a, 29.30.-h
The expected spectrum is shown in Fig. 3. Predicted spectrum in Fig. 2 and the ratio of these data to observed energy spectrum of the events from the low-energy configuration alone, the number of events observed in the data is 730, to be compared with an expectation of 936±53 (syst.). The observed energy spectrum of the events from the low- and high-energy datasets is shown along with the predicted spectrum in Fig. 2 and the ratio of these data to the expected spectrum is shown in Fig. 3.

Under the assumption the observed deficit is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations [1], a fit is performed to extract the parameters $|\Delta m^2|$ and $\sin^2(2\theta)$ [15] using the expression

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{|\Delta m^2|L}{E}\right),$$

where $L$[km] is the distance from the target, $E$[GeV] is the neutrino energy, and $|\Delta m^2|$ is measured in eV$^2$. The FD data from Run I, Run II, and the high-energy run are separately fit to Eq. 1. The best-fit parameters minimize the $\chi^2$ expression given in [2]. The predicted oscillated spectrum includes the contamination from $\nu_\tau$ produced in the oscillation process.

In fitting the data to Eq. 1 $\sin^2(2\theta)$ was constrained to lie in the physical region. To reduce the effect of dominant systematic uncertainties in Table II(a) and (c) for $|\Delta m^2|$ , and (d) for $\sin^2(2\theta)$ these systematic uncertainties were included as nuisance parameters in the fit. The resulting best fit to the neutrino energy spectrum is shown in Fig. 2 and Fig. 3. We obtain $|\Delta m^2| = (2.43\pm0.13)\times10^{-3}$ eV$^2$ and $\sin^2(2\theta) > 0.95$ at 68% confidence level (C.L.) [15]. The fit $\chi^2=90$ for 97 degrees of freedom. The resulting 68% C.L. ($\Delta \chi^2=2.30$)
The dominant uncertainties are incorporated as nuisance parameters in the fit of our data to Eq. 1 so as to reduce their effect on the oscillation parameter measurement (see text). The values are the average shifts for varying the parameters in both directions without imposing the constraint on the fit. Correlations between the systematic effects are not taken into account. The dominant uncertainties are incorporated as nuisance parameters in the fit of our data to Eq. 1 so as to reduce their effect on the oscillation parameter measurement (see text).

and 90% C.L. (Δχ²=4.61) intervals for the oscillation parameters |Δm²| and sin²(2θ). The values are the average shifts for varying the parameters in both directions without imposing the constraint on the fit. Correlations between the systematic effects are not taken into account. The dominant uncertainties are incorporated as nuisance parameters in the fit of our data to Eq. 1 so as to reduce their effect on the oscillation parameter measurement.

Fig. 3 also shows that the previous MINOS result [2] is in good agreement with the current measurement. Taken alone, the Run II data yield |Δm²|=(2.32+0.17−0.16)×10⁻³ eV² and sin²(2θ)=1.0, to be compared with (2.57±0.24)×10⁻³ eV² and sin²(2θ)=1.0 from Run I. The two results are consistent at 68% C.L. We note that the value of 2.57×10⁻³ eV² for Run I differs from that quoted in [2] because of our improved reconstruction and selection of charged-current events and improved MC simulation of neutrino interactions.

We have also fit the FD energy spectra to alternative models that have been proposed to explain the disappearance of neutrinos in flight, namely, the decay of neutrinos to lighter particles (Eq. 13 of [4]), and the decoherence of the neutrino’s quantum-mechanical wave packet (Eq. 5 of [5]). Fig. 3 shows the ratios of the energy spectra arising from our best fits to these alternative models to the prediction of the FD spectrum in the absence of νμ disappearance. The χ² for the best fit to the decay model is 104/97 d.o.f., while that for the decoherence model is 123/97 d.o.f. Given the Δχ² = 14 and 33 of these two models relative to the oscillation hypothesis, these models are disfavored with respect to the oscillation hypothesis at the 3.7 and 5.7 standard-deviation levels.

In summary, we have presented updated measurements of neutrino oscillation parameters from the MINOS experiment. Based upon an exposure of 3.36×10²⁰ POT from the NuMI beam, we obtain |Δm²| = (2.43 ± 0.13)×10⁻³ eV² (68% C.L.) and mixing angle sin²(2θ) > 0.90 (90% C.L.). As the dataset presented here includes the subset analyzed in [2], these results supersede our previous publication. Our data disfavor two alternative explanations for disappearance of neutrinos in flight, namely neutrino decays [3] into lighter particles and quantum decoherence of neutrinos [5] at the 3.7 and 5.7 standard-deviation level, respectively.

This work was supported by the US DOE; the UK STFC; the US NSF; the State and University of Minnesota; the University of Athens, Greece; and Brazil’s FAPESP and CNPq. We are grateful to the Minnesota Department of Natural Resources, the crew of the Soudan Underground Laboratory, and the staff of Fermilab for their contribution to this effort.

TABLE I: Sources of systematic uncertainties in the measurement of |Δm²| and sin²(2θ). The values are the average shifts for varying the parameters in both directions without imposing the constraint on the fit. Correlations between the systematic effects are not taken into account. The dominant uncertainties are incorporated as nuisance parameters in the fit of our data to Eq. 1 so as to reduce their effect on the oscillation parameter measurement (see text).

| Uncertainty          | |Δm²| (10⁻³ eV²) | sin²(2θ) |
|----------------------|----------------|-----------|
| (a) Abs hadronic E scale (± 10.3%) | 0.052 | 0.004 |
| (b) Rel hadronic E scale (± 3.3%) | 0.027 | 0.006 |
| (c) Normalization (± 4%) | 0.081 | 0.001 |
| (d) NC contamination (± 50%) | 0.021 | 0.016 |
| (e) μ momentum (range 2%, curv 3%) | 0.032 | 0.003 |
| (f) σμ(Eµ < 10 GeV) (±12%) | 0.006 | 0.004 |
| (g) Beam flux | 0.010 | 0.000 |
| Total Systematic Uncertainty | 0.108 | 0.018 |
| Expected Statistical Uncertainty | 0.19 | 0.09 |

* Deceased.

FIG. 4: Contours for the oscillation fit to the data in Fig. 3, including systematic errors. Also shown are contours from previous experiments \[17, 18\] and our earlier result \[2\].

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Fermilab-Conf-05-093-AD and \texttt{arXiv:physics/0508001}
[13] The experiment measures an unresolved mixture of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$, which we refer to as $|\Delta m^2|$ for brevity. The parameter $\sin^2(2\theta)$ is likewise an admixture. For further discussion see G. L. Fogli et al., Prog. Part. Nucl. Phys. 57, 742 (2006).
[15] Although the contours in Fig. 4 are calculated with two degrees of freedom (d.o.f.), the parameter errors are calculated with only one d.o.f. as in \[1\] using $\Delta \chi^2 = 1$ and 2.71, respectively.
[16] The effect of the constraint to the physical region was investigated using the unified approach of G.J. Feldman and R.D. Cousins, Phys. Rev. D57, 3873, (1998), which gave slightly smaller confidence intervals.
[19] Approximately 5% of $\nu_\mu$ interactions occur in aluminum and scintillator.