Search for Active Neutrino Disappearance Using Neutral-Current Interactions in the MINOS Long-Baseline Experiment

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We report the first detailed comparisons of the rates and spectra of neutral-current neutrino interactions at two widely separated locations. A depletion in the rate at the far site would indicate mixing between ν_μ and a sterile particle. No anomalous depletion in the reconstructed energy spectrum is observed. Assuming oscillations occur at a single mass-squared splitting, a fit to the neutral- and charged-current energy spectra limits the fraction of ν_μ oscillating to a sterile neutrino to be below 0.68 at 90% confidence level. A less stringent limit due to a possible contribution to the measured neutral-current event rate at the far site from ν_e appearance at the current experimental limit is also presented.

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Several experiments observing charged-current (CC) interactions of neutrinos have provided compelling evidence for ν_μ and ν_e disappearance as the neutrinos propagate from the point of production [1–5]. The Super-Kamiokande experiment has reported extensively on the disappearance of ν_μ produced in the atmosphere [2]. Measurements of solar ν_e showed that the disappearance of those neutrinos is due to matter enhanced conversions [3]. The KamLAND reactor experiment provided clear evidence for $\bar{\nu}_e$ mixing [4].

These results are conventionally interpreted as mixing among the active neutrino flavors that couple to the electroweak current. Precise measurements of the Z boson decay width indicate there are only three light active neutrinos [6], but they do not exclude the existence of ''sterile'' neutrinos ν_s that do not couple to the electroweak current. Sterile neutrinos could help resolve several outstanding problems in particle physics and astrophysics. For example, sterile neutrinos with masses on the order of 1 eV can participate in the seesaw mechanism to introduce neutrino masses [7] and can also aid in heavy element nucleosynthesis in supernovae [8]. The SNO experiment has shown that the total flux of active neutrinos from the sun agrees with the expectation from solar models [9], thereby limiting the extent to which the first or second neutrino mass eigenstates could couple to a sterile neutrino. While the Super-Kamiokande experiment excludes pure $\nu_\mu \rightarrow \nu_s$ and favors pure $\nu_\mu \rightarrow \nu_\tau$ oscillations in its analysis of atmospheric neutrinos, an admixture of the two possibilities is allowed [10] and has attracted considerable attention in the literature [11].

The MINOS experiment has reported a significant deficit of ν_μ at its far detector relative to the near detector through measurement of the rate of ν_μ CC interactions [5,12]. If this deficit is due solely to conversions of ν_μ to $\nu_\tau + \nu_e$, then the rate of neutral-current (NC) interactions at the far detector remains unchanged from the nonoscillation prediction. Alternatively, if any ν_μ convert to a sterile state, then the NC rate would be suppressed and the reconstructed energy spectrum would be distorted. In this Letter we report the first measurement of the total active neutrino rate using a precisely known long baseline and neutrinos produced with an accelerator. The reconstructed energy spectra for NC and CC interactions are used to limit the fraction of ν_μ converting to ν_s by fitting them to a model of oscillations between ν_μ, ν_τ, ν_e, and ν_s dominated by the atmospheric mass-squared splitting.

The neutrino beam is produced using 120 GeV/c protons from the Fermilab Main Injector incident on a graphite target, which is followed by two magnetic focusing horns. The flavor composition of the beam is 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, and 1.3% $\nu_e + \bar{\nu}_e$. In this analysis the ν and $\bar{\nu}$ are assumed to oscillate with the same parameters. The data used in this analysis come from the low-energy beam configuration whose peak neutrino energy is 3.3 GeV [5,12], with an exposure of the far detector to 2.46×10^{20} protons on target.

The 0.98 kt near detector is located 1.04 km downstream of the target and lies 103 m underground at Fermilab. The 5.4 kt far detector is 734 km downstream of the near detector and is located in the Soudan Underground Laboratory in Minnesota, 705 m below the surface. The fiducial masses used for the near and far detectors are 27 ton and 3.8 kt, respectively.

The MINOS detectors are steel scintillator tracking calorimeters [13]. The vertically oriented detector planes are composed of 2.54 cm thick steel and 1 cm thick plastic scintillator. The scintillator layer is composed of 4.1 cm wide strips. The near (far) detector is magnetized to an average toroidal field of 1.3 (1.4) T.

Hadronic showers resulting from NC interactions generate scintillation light in an average of 12 strips for 1 GeV of deposited energy. Events must have at least 4 strips with signal in order to be considered in the analysis. Individual scintillator strips are grouped into either reconstructed tracks or showers, which are combined into events. The vertex for each event is required to be sufficiently far from any edge of the detector to ensure that the final-state hadronic showers are well contained within the fully sampled portion of the detectors.

The near detector data are used to predict the number of expected events in the far detector, but the ability to make

this prediction is complicated by the high rate environment at the near detector. At an intensity of 2.2×10^{13} protons on target, an average of 16 neutrino interactions are produced in the near detector for each spill [5]. The reconstruction program separates individual neutrino interactions that occur within the same spill. This initial pass overestimates the number of NC interactions having reconstructed energy, E_{reco}, <1 GeV by 36%; above 1 GeV the estimate is as expected. Additional selections making use of event topology and timing are then used to decrease this background. Events must be separated by at least 40 ns, and events that occur within 120 ns of each other must have vertices separated by at least 1 m in the longitudinal direction [14]. After applying these criteria, the remaining background from poorly reconstructed events with $E_{\text{reco}} < 1$ GeV is 7%.

The rate of neutrino interactions from the neutrino beam in the far detector is much lower than in the near detector, with approximately 1 interaction for every 10^4 spills. Interactions from the beam neutrinos are identified using a window around the global positioning system time stamp of the spills of $-2 < t < 12$ μs, where $t = 0$ is the expected start time of the 10 μs spill at the far detector. Given the low rate of neutrino interactions in the far detector, spurious events that are coincident with the beam spills from noise, cosmic-ray muons, or poor event reconstruction can introduce backgrounds to the analysis. Additional criteria are used to remove such events, leaving a residual background of <1% of the signal [15].

Charged-current interactions are identified by the presence of a track that may or may not be associated with a shower. Neutral-current interactions typically have a single hadronic shower, although the reconstruction may identify a track in the event; such tracks could come from pions, but are mostly reconstruction artifacts. An event is classified as NC-like if it has a reconstructed shower, is shorter than 60 planes, and has no track extending more than 5 consecutive planes beyond the shower [16]. The principal background in the spectrum of NC-like events comes from highly inelastic ν_μ-CC interactions. The E_{reco} spectrum of NC-like events in the near detector is shown in Fig. 1.

The Monte Carlo simulation is used to make an initial estimate of the ratio of event yields in the far and near detectors as a function of E_{reco}. This ratio is multiplied by the observed energy spectrum in the near detector to produce a far detector prediction of the NC-like event spectrum. The true energy of the simulated neutrinos in each reconstructed energy bin of the prediction is used to determine the effect of oscillations for that range of reconstructed energy. To avoid biases, the methods for identifying NC-like events and predicting the far detector spectrum were developed using only the near detector data and Monte Carlo simulation. The analysis procedures were finalized prior to examining far detector data.

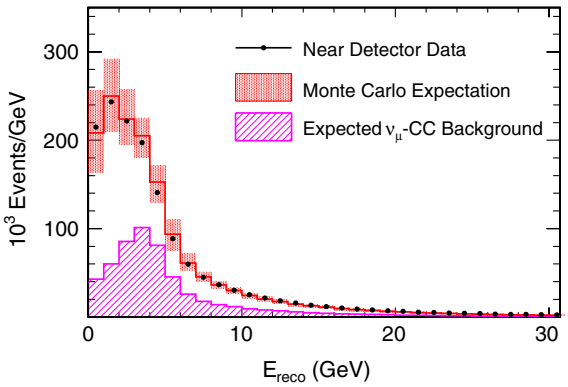

FIG. 1 (color online). The reconstructed energy spectrum for NC-like events in the near detector. Data (solid points) are shown superposed on the total Monte Carlo expectation including systematic uncertainties (solid line with shaded band). The hatched distribution shows the ν_μ-CC background as determined by the simulation.

Figure 2 shows the measured and predicted E_{reco} spectra at the far detector. The spectra are compared using a statistic, R, which expresses the agreement between the predicted and observed number of events:

$$R \equiv \frac{N_{\text{data}} - B_{\text{CC}}}{S_{\text{NC}}}, \tag{1}$$

where, within a given energy range, N_{data} is the measured event count, B_{CC} is the extrapolated CC background from all flavors, and S_{NC} is the extrapolated number of NC interactions. The values of S_{NC} and contributions to B_{CC} are calculated in the framework of three neutrino oscillations and are shown in Table I. Because the disappearance of ν_μ occurs mainly for true neutrino energies <6 GeV [12], the data are separated into two samples. Events with $E_{\text{reco}} < 3$ GeV are grouped into a low-energy sample while events with $3 < E_{\text{reco}} < 120$ GeV are grouped into a high-

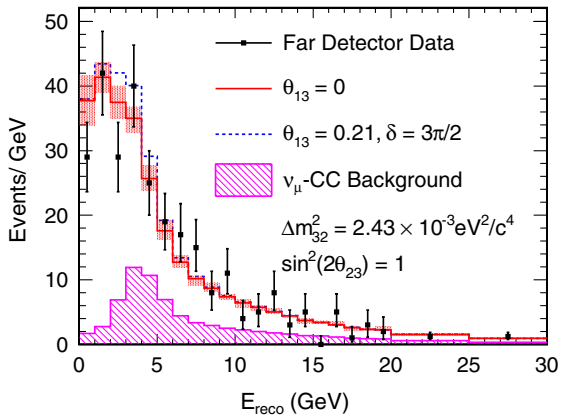

FIG. 2 (color online). Spectrum of observed NC-like events in the far detector with predictions for the two oscillation hypotheses described in the text. The filled regions in each bin indicate the systematic uncertainty in the predicted rates.

TABLE I. Values of R, N_{data}, S_{NC}, and the contributions to B_{CC} for various reconstructed energy ranges. The numbers in parentheses are calculated including ν_e appearance at the upper limit discussed in the text.

E_{reco} (GeV)	N_{data}	S_{NC}	$B_{\text{CC}}^{\nu_\mu}$	$B_{\text{CC}}^{\nu_\tau}$	$B_{\text{CC}}^{\nu_e}$
0–3	100	101.1	11.2	1.0	1.8 (9.3)
3–120	191	98.0	64.2	3.5	11.8 (24.6)
0–3	$R = 0.85 \pm 0.10 \pm 0.07$				$(0.78 \pm 0.10 \pm 0.07)$
3–120	$R = 1.14 \pm 0.14 \pm 0.10$				$(1.02 \pm 0.14 \pm 0.10)$
0–120	$R = 0.99 \pm 0.09 \pm 0.07$				$(0.90 \pm 0.09 \pm 0.08)$

energy sample. The median true neutrino energies of the low and high energy samples are 3.1 and 7.9 GeV, respectively. The values of R calculated for these ranges in E_{reco} are shown in Table I. In the region with $E_{\text{reco}} < 3$ GeV, R differs from 1 by 1.3σ. Over the full energy range, 0–120 GeV, the depletion of the total NC event rate is limited to be below 17% at 90% confidence level.

The principal sources of systematic uncertainty in R are listed in Table II. The absolute scale of the hadronic energy is known to within 12%, of which 10% reflects uncertainties in the final-state interactions in the nucleus and 6% results from uncertainty in the detector response to single hadrons. The relative calibration of the hadronic energy between the detectors has an uncertainty of 3% [5], and the relative normalization between them has an uncertainty of 4%. The uncertainty in the near detector event count due to the selection criteria is 15% for $E_{\text{reco}} < 0.5$ GeV, 3% for events with $0.5 < E_{\text{reco}} < 1$ GeV, and is negligible for $E_{\text{reco}} > 1$ GeV. Table II shows the effect of these uncertainties on R.

The uncertainty on the size of the ν_μ-CC background was determined by comparing the near detector NC-like reconstructed energy spectrum from the low-energy beam configuration used in this analysis with the spectra from three other beam configurations having higher average neutrino energy. In each reconstructed energy bin, i, of the low-energy beam the total number of events is the sum of the NC and CC interactions, $N_i = \text{NC}_i + \text{CC}_i$. The quantity r_i^{NC} (r_i^{CC}) is the ratio of the number of NC (CC) interactions in each energy bin in an alternative beam configuration to the corresponding number in the low-energy beam configuration. The value of CC_i can be calculated from the spectrum in another beam,

$$\text{CC}_i = \frac{r_i^{\text{NC}} N_i - N_i^A}{r_i^{\text{NC}} - r_i^{\text{CC}}}, \tag{2}$$

where N_i^A is the total number of events observed in the alternate beam configuration. The values of r_i^{NC} and r_i^{CC} are taken from the Monte Carlo simulation. The uncertainty in the ν_μ-CC background is taken as the difference between the uncertainty-weighted average value of CC_i measured using the different beam configurations and the value predicted by the Monte Carlo simulation. That difference is consistent within 15% for all reconstructed energies. The size of the ν_μ-CC background at the far detector depends on the parameters for $\nu_\mu \rightarrow \nu_\tau$ oscillations used in the prediction. The MINOS measured values of $\Delta m_{32}^2 = 2.43 \times 10^{-3}$ eV$^2/c^4$ and $\theta_{23} = \pi/4$ [12] were used for the prediction, and variations within the 1σ range of these parameters change the ν_μ-CC background in the far detector by less than 10%.

Because the selection criteria identify ν_e-CC interactions as NC-like with nearly 100% efficiency, the background from ν_e inherent in the beam and $\nu_\mu \rightarrow \nu_e$ oscillations is also considered. An upper limit for the ν_e-CC rate in the far detector was estimated using the normal mass hierarchy with $\theta_{13} = 0.21$ rad and $\delta = 3\pi/2$ rad. The choice of θ_{13} corresponds to the 90% confidence level upper limit for the MINOS measured value of Δm_{32}^2 [17]. The contribution to B_{CC} from ν_e and the values of R under these assumptions are shown in Table I.

The data shown in Fig. 2 are combined with the data from CC interactions to determine the fraction of the previously observed ν_μ disappearance that could be due to oscillations between active and sterile neutrinos. The data are fit to a model that assumes oscillations between ν_μ, ν_τ, and ν_s occur at a single mass-squared splitting. The probabilities for ν_μ to remain ν_μ or convert to ν_s are

$$\begin{aligned} P_{\nu_\mu \rightarrow \nu_\mu} &= 1 - \alpha_\mu \sin^2(1.27 \Delta m^2 L/E) \\ \text{and} \quad P_{\nu_\mu \rightarrow \nu_s} &= \alpha_s \sin^2(1.27 \Delta m^2 L/E), \end{aligned} \tag{3}$$

where Δm^2 is the atmospheric mass-squared splitting in eV$^2/c^4$, $L = 735$ km, E is the neutrino energy in GeV, and α_μ and α_s are phenomenological parameters related to the mixing angles. A simultaneous fit to the NC-like and ν_μ-CC energy spectra yields the energy independent fraction of ν_μ oscillating to ν_s,

$$f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} = 0.28^{+0.25}_{-0.28}(\text{stat} + \text{syst}), \tag{4}$$

with $\chi^2 = 46.5$ for 43 degrees of freedom and $f_s < 0.68$ at 90% confidence level. The fit includes the systematic un-

TABLE II. Sources of systematic uncertainties considered in this analysis and their effect on R.

	0–3 GeV	3–120 GeV
Absolute E_{had}	$\pm < 0.01$	± 0.05
Relative E_{had}	± 0.03	± 0.04
Normalization	± 0.04	± 0.08
Near detector selection	± 0.02	$\cdots$
ν_μ-CC background	± 0.03	± 0.01
Total	± 0.07	± 0.10

certainties in Table II as nuisance parameters. Including electron neutrino appearance at the previously discussed upper limit results in $f_s = 0.43^{+0.23}_{-0.27}(\text{stat} + \text{syst})$ with $\chi^2 = 46.6$ and $f_s < 0.80$ at 90% confidence level. The χ^2 values for $f_s = 0$ are 47.4 without ν_e appearance and 49.0 with ν_e appearance.

In summary, we have reported the first measurements of neutrino neutral-current rates and spectra in an accelerator long-baseline neutrino experiment. The rates at the near and far detectors are consistent with expectations from decay kinematics and geometry, providing new support for the interpretation of muon neutrino disappearance as oscillations among the three active neutrinos. This result provides one of the best limits to date on the fraction of muon neutrinos which may convert to sterile neutrinos in oscillations associated with the atmospheric mass-squared splitting.

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