Search for Lorentz Invariance and CPT Violation with the MINOS Far Detector


(MINOS Collaboration)

1Argonne National Laboratory, Argonne, Illinois 60439, USA
2Department of Physics, University of Athens, GR-15771 Athens, Greece
3Physics Department, Benedictine University, Lisle, Illinois 60523, USA
4Brookhaven National Laboratory, Upton, USA
5Lauritsen Laboratory, California Institute of Technology, Pasadena, California 91125, USA
6Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom
7Universidade 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
10Instituto de Fisica, Universidade Federal de Goiás, CP 131, 74001-970, Goiânia, GO, Brazil
11Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
12Holy Cross College, Notre Dame, Indiana 46556, USA
13Physics Division, Indiana Institute of Technology, Chicago, Illinois 60616, USA
14Indiana University, Bloomington, Indiana 47405, USA
15Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011 USA
16Institute for High Energy Physics, Protvino, Moscow Region RU-140284, Russia
17Nuclear Physics Department, Lebedev Physical Institute, Leninsky Prospect 53, 119991 Moscow, Russia
18Lawrence Livermore National Laboratory, Livermore, California 94550, USA
19Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom
20University of Minnesota, Minneapolis, Minnesota 55455, USA
21Department of Physics, University of Minnesota–Duluth, Duluth, Minnesota 55812, USA
22Otterbein College, Westerville, Ohio 43081, USA
23Subdepartment of Particle Physics, University of Oxford, Oxford OX1 3RH, United Kingdom
24Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
25Rutherford Appleton Laboratory, Science and Technologies Facilities Council, OX11 0QX, United Kingdom
26Instituto de Fisica, Universidade de São Paulo, CP 66318, 05315-970, São Paulo, SP, Brazil
27Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208, USA
28Department of Physics, Stanford University, Stanford, California 94305, USA
29Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
30Physics Department, Texas A&M University, College Station, Texas 77843, USA
31Department of Physics, University of Texas at Austin, 1 University Station C1600, Austin, Texas 78712, USA
32Physics Department, Tufts University, Medford, Massachusetts 02155, USA
33Department of Physics, Warsaw University, Hoża 69, PL-00-681 Warsaw, Poland
34Physics Department, Western Washington University, Bellingham, Washington 98225, USA

PRL 105, 151601 (2010) PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2010

0031-9007/10/151601(5) 151601-1 © 2010 The American Physical Society
Neutrinos have provided many crucial insights into particle physics, including the existence of physics beyond the minimal standard model with the detection of neutrino oscillations [1,2]. Because oscillations are interferometric in nature, they are sensitive to other indicators of new physics. Such indicators include potential small amplitude signals persisting to the current epoch whose origin is a fundamental theory that unifies quantum physics and gravity at the Planck scale $m_p \approx 10^{19}$ GeV. One promising category of Planck-scale signals is the violation of the Lorentz and $CPT$ symmetries that are central to the standard model and general relativity. The standard-model extension (SME) is the comprehensive effective field theory that describes Lorentz ($LV$) and $CPT$ violation (CPTV) at attainable energies [3].

The SME predicts behaviors for neutrino flavor change that are different from conventional neutrino oscillation theory. The probability of flavor change in the SME depends on combinations of $L$, the distance traveled by the neutrino, and the product of distance and the neutrino energy, $L \times E_\nu$. For conventional oscillation theory the transition probability depends only on $L/E_\nu$. The SME also predicts that the neutrino flavor change probability depends on the angle between the direction of the neutrino and the $LV/CPTV$ field in the Sun-centered inertial frame in which the SME is formulated [4]. Experiments like MINOS [5], whose neutrino beam is fixed on Earth, are well suited to search for this behavior, which would appear as a periodic variation in the detected neutrino rate as the beam swings around the field with the sidereal frequency $\omega_\Phi = 2\pi / (23^556^{sec}04.09053^s)$.

MINOS has a near detector (ND) located 1 km from the neutrino beam source and a far detector (FD) located 735 km from the neutrino source. Because of their different baselines, the ND and FD are sensitive to two separate limits of the general SME formulated for the neutrino sector. The predicted SME effects for baselines less than 1 km are independent of neutrino mass [4], and both MINOS [6] and LSND [7] reported searches for these effects. Recent theoretical work has shown that SME effects are a perturbation to the dominant mass oscillations for neutrinos having the appropriate $L/E_\nu$ to experience oscillations [8]. Since the probability for transitions due to $LV$ increases with the baseline, experiments with baselines greater than $\approx 100$ km are especially sensitive to $LV$ and CPTV. The following analysis using MINOS FD data is the first search for perturbative $LV$ and CPTV effects in an admixture with neutrino oscillations.

According to the SME, the transition probability for $\nu_\mu \rightarrow \nu_\tau$ transitions over long baselines is $P_{\mu\tau} = P_{\mu\tau}^{(0)} + \tilde{P}_{\mu\tau}$, where $P_{\mu\tau}^{(0)}$ is the conventional mass oscillation probability for transitions between two flavors and $\tilde{P}_{\mu\tau}$ is the perturbation due to $LV$ and CPTV, with $P_{\mu\tau}^{(0)}/P_{\mu\tau} \ll 1$. In the SME, $P_{\mu\tau}^{(0)}$ is given by [8]

$$
P_{\mu\tau}^{(0)} = 2L\left\{ \left( P_{C}^{(1)} \right)_{\tau\mu} + \left( P_{A}^{(1)} \right)_{\tau\mu} \sin \omega_\Theta T_\Theta + \left( P_{A}^{(1)} \right)_{\tau\mu} \cos \omega_\Theta T_\Theta + \left( P_{B}^{(1)} \right)_{\tau\mu} \sin 2\omega_\Theta T_\Theta + \left( P_{B}^{(1)} \right)_{\tau\mu} \cos 2\omega_\Theta T_\Theta \right\}, \tag{1}
$$

where $L = 735$ km is the distance from neutrino production in the NuMI beam to the MINOS FD [2], $T_\Theta$ is the local sidereal time (LST) at neutrino detection, and the coefficients $(P_{C}^{(1)})_{\tau\mu}$, $(P_{A}^{(1)})_{\tau\mu}$, $(P_{A}^{(1)})_{\tau\mu}$, $(P_{B}^{(1)})_{\tau\mu}$, and $(P_{B}^{(1)})_{\tau\mu}$ contain the $LV$ and CPTV information. These coefficients depend on the SME coefficients that explicitly describe $LV$ and CPTV, $(a_L)_{\tau\mu}$ and $(c_L)_{\tau\mu}$, as well as the neutrino mass-squared splitting $\Delta m^2_{32}$ [8]. For two-flavor transitions, only the real components of the $(a_L)_{\tau\mu}$ and $(c_L)_{\tau\mu}$ contribute to the transition probability.

The magnitudes of the functions in Eq. (1) depend on the direction of the neutrino propagation in a fixed coordinate system on the rotating Earth. The direction vectors are defined by the colatitude of the NuMI beam line $\chi = (90^\circ$ latitude) = 42.17973347$^s$, the beam zenith angle $\theta = 86.7255^\circ$ defined from the $z$ axis, which points up toward the local zenith, and the beam azimuthal angle $\phi = 203.909^\circ$ measured counterclockwise from the $x$ axis chosen to lie along the detector’s long axis.

This analysis selected data by using standard MINOS beam quality requirements and data quality selections [2,9]. The neutrino events used must interact in the 4.0 kt FD fiducial volume [9] and be charged-current (CC) in nature. The selection method described in Ref. [9] allowed
the identification of the outgoing muon in a CC interaction. As in Ref. [6], we focused on these events to maximize the $\nu_\mu$ disappearance signal.

The data used come from the run periods listed in Table I; also shown are the number of protons incident on the neutrino production target (POT) for each period and the total number of events observed. To avoid biases, we performed the analysis blindly with the procedures determined by using only the runs I and II data. The run III data, comprising more than 50% of the total, were included only after finalizing the analysis procedures.

We tagged each neutrino event with the time determined by the Global Positioning System (GPS) receiver located at the FD site that reads out absolute universal coordinated time and is accurate to 200 ns [10]. The GPS time of the accelerator extraction magnet signal defined the time of the beam spill. We converted the time of each neutrino event and spill to local sidereal time (LST) in standard ways [11]. The uncertainty in the GPS time stamps introduced no significant systematic error into the analysis [6]. We placed each detected CC event into a histogram that ranged from 0 to 1 in the local sidereal phase (LSP), the LST of the event divided by the length of a sidereal day. We used the LSP for each spill to place the POT for each instance into another set of histograms. We drew the phases for each event and spill randomly from the LSP histogram of the start times for all spills. Dividing an event histogram by a POT histogram included only after finalizing the analysis procedures.

By dividing these two histograms, we obtained the normalized neutrino event rate as a function of the LSP, in this case, up to $C_2^2$ only into the Fourier terms $R_{ij}$, with the weighted mean rate for that bin, $\bar{R}_i$. The distribution of $r = (\bar{R}_{ij} - \bar{R}_j)/\sigma_{ij}$, where $\sigma_{ij}$ is the statistical uncertainty in $\bar{R}_{ij}$ for all $i$ and $j$, is Gaussian with $\bar{r} = 0$ and $\sigma = 1$, as expected for statistically consistent runs. Given this result, we combined the runs into a single data set whose rate as a function of the LSP is shown in Fig. 2. The distribution of $\bar{R}_i$ was tested by comparing the rate for run $i$ in LSP phase bin $j$, $R_{ij}$, with the weighted mean rate for that bin, $\bar{R}_i$. The distribution of $r = (R_{ij} - \bar{R}_j)/\sigma_{ij}$, where $\sigma_{ij}$ is the statistical uncertainty in $R_{ij}$ for all $i$ and $j$, is Gaussian with $\bar{r} = 0$ and $\sigma = 1$, as expected for statistically consistent runs. Given this result, we combined the runs into a single data set whose rate as a function of the LSP is shown in Fig. 1. The mean rate is $2.36 \pm 0.06$ events per $10^{18}$ POTs, and the uncertainties shown in the figure are statistical.

TABLE I. Run parameters.

<table>
<thead>
<tr>
<th>Run dates</th>
<th>POTs</th>
<th>CC events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I</td>
<td>May05–Feb06</td>
<td>$1.24 \times 10^{20}$</td>
</tr>
<tr>
<td>Run II</td>
<td>Sep06–Jul07</td>
<td>$1.94 \times 10^{20}$</td>
</tr>
<tr>
<td>Run III</td>
<td>Nov07–Jun09</td>
<td>$3.88 \times 10^{20}$</td>
</tr>
</tbody>
</table>

We searched for a sidereal signal by looking for excess power in the FFT of the data in Fig. 1 at the frequency corresponding to exactly 1 sidereal day. We used two statistics in our search: $p_1 = \sqrt{S_1^2 + C_1^2}$ and $p_2 = \sqrt{S_2^2 + C_2^2}$, where $S_1^2$ is the power returned by the FFT for $\sin(\omega_0 T_0)$, $C_1^2$ is the power returned for $\cos(\omega_0 T_0)$, and $S_2^2$ and $C_2^2$ are the analogous powers for the second harmonics. We used the quadratic sum of powers to minimize the effect of the arbitrary choice of zero point in the phase at $0^h$ LST. Table II gives the $p_1$ and $p_2$ values returned by the FFT for the total data set.

We determined the significance of our measurements of $p_1$ and $p_2$ by simulating $10^4$ experiments without a sidereal signal. To construct these experiments we used the data themselves by randomizing the LSP of each CC event $10^4$ times and placing each instance into a different phase histogram. We used the LSP for each spill to place the POT for each instance into another set of histograms. We drew the phases for each event and spill randomly from the LSP histogram of the start times for all spills. Dividing an event histogram by a POT histogram produced one simulated experiment. The randomization of both the spill and event LSPs removed any potential sidereal variation from the data.

We performed the FFT on the simulated experiments and computed the $p_1$ and $p_2$ statistics for each. The resulting distributions of $p_1$ and $p_2$ are nearly identical as shown in Fig. 2. The third column of Table II gives the probability $P_F$ that the harmonic powers we found were due to statistical fluctuations. $P_F$ is the probability of drawing a value of $p_1$ or $p_2$ from the parent distribution in Fig. 2 at least as large as found in the data.

TABLE II. Results for the $p_1$ and $p_2$ statistics from a FFT of the data in Fig. 1. The third column gives the probability $P_F$ that the measured value is due to a statistical fluctuation.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>$p$(FFT)</th>
<th>$P_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>1.09</td>
<td>0.26</td>
</tr>
<tr>
<td>$p_2$</td>
<td>1.13</td>
<td>0.24</td>
</tr>
</tbody>
</table>
could have introduced a false signal. However, systematic differences between the day and night event rates were smaller than the statistical errors in the rates themselves and could not introduce a false signal. Atmospheric effects could also have imprinted a sidereal signal on the data if there were a solar diurnal modulation in the event rate that beats with a yearly modulation [13]. Using methods described in Ref. [14], we found that this false sidereal signal is < 0.2% of the mean event rate and well below the detection threshold.

Since we found no sidereal signal, we determined upper limits on the \((a_L)_{\mu T}\) and \((c_L/\mu)^2\) coefficients that describe LV and CPTV in the SME. Coefficients where both \(\alpha\) and \(\beta\) are either \(T\) or \(Z\) cannot introduce a sidereal variation, and as such this experiment is not sensitive to them.

Neutrinos are simulated by using the standard MINOS Monte Carlo simulation [2] that models the NuMI beam line, including the hadron production and subsequent propagation through the focusing elements, hadron decay in the 675 m decay pipe, and the probability that any neutrinos produced will intersect the FD 735 km away. These neutrinos, along with weights determined by decay kinematics, are used in the detailed simulation of the FD. We chose \(|\Delta m^2_{32}| = 2.43 \times 10^{-3} \text{ eV}^2\) and \(\sin^2(2\theta_{23}) = 1\), the values measured by MINOS [2], for the simulation. Our tests show that changing these values within the allowed uncertainty does not alter the limits we found.

We determined the limits for each SME coefficient individually. We constructed a set of experiments in which one coefficient was set to be small but nonzero and the remaining coefficients were set to zero. We simulated a high statistics event histogram by picking events with a random sidereal phase drawn from the distribution of start times for the data spills and weighted these simulated events by both their survival probability and a factor to account for the different exposures between the data and the simulation. Simultaneously, we simulated a spill histogram by entering the average number of POTs required to produce one event in the FD, as determined from the data, at the sidereal phase of each simulated event. The division of these two histograms resulted in the LSP histogram we used to compute the \(p_1\) and \(p_2\) statistics. We then increased the magnitude of the nonzero SME coefficient and repeated the process until either \(p_1\) or \(p_2\) was greater than the 2.26 detection threshold. To reduce fluctuations we computed the limit 100 times and averaged the results. Table III gives the mean magnitude of the coefficient required to produce a signal above threshold. This procedure could miss fortuitous cancellations of SME coefficients. We did not consider these cases.

We cross-checked these limits by simulating 750 low statistics experiments for each coefficient limit given in Table III. Each experiment had the same total number of neutrinos as the data and thus represents the statistical fluctuations in the data. The distributions of the \(p_1\) and \(p_2\) statistics for all the experiments were used to determine
TABLE III. 99.7% C.L. limits on SME coefficients for $\nu_\mu \rightarrow \nu_\tau$; $(a_L)_{\mu\tau}^\mu$ have units [GeV]; $(c_L)_{\mu\tau}^\mu$ are unitless. The columns labeled $I$ show the improvement from the near detector limits.

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>Limit</th>
<th>$I$</th>
<th>Coeff.</th>
<th>Limit</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(a_L)_{\mu e}^{\mu e}$</td>
<td>$5.9 \times 10^{-23}$</td>
<td>510</td>
<td>$(a_L)_{\mu e}^{\mu e}$</td>
<td>$6.1 \times 10^{-23}$</td>
<td>490</td>
</tr>
<tr>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$0.5 \times 10^{-23}$</td>
<td>20</td>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$0.5 \times 10^{-23}$</td>
<td>20</td>
</tr>
<tr>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$2.5 \times 10^{-23}$</td>
<td>220</td>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$2.4 \times 10^{-23}$</td>
<td>230</td>
</tr>
<tr>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$1.2 \times 10^{-23}$</td>
<td>230</td>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$0.7 \times 10^{-23}$</td>
<td>170</td>
</tr>
<tr>
<td>$(c_L)_{\mu e}^{\mu e}$</td>
<td>$0.7 \times 10^{-23}$</td>
<td>190</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

The confidence level at which the measured values in Table II are excluded by each limit. The exclusion using this method is >99.7% C.L. for all coefficients.

In summary, we found no evidence for sidereal variations in the neutrino rate in the MINOS FD. This result, when framed in the SME [4,8], leads to the conclusion that we have detected no evidence for the violation of Lorentz or CPT invariance described by this framework for neutrinos traveling over the 735 km baseline from their production in the NuMI beam to the MINOS FD. The limits on the SME coefficients in Table III for the FD that come from this null result improve the limits we found for the ND by factors of the order of 20–510 [6]. This improvement is due to the different behavior of the oscillation probability in the short and long baseline approximations coupled with the significantly increased baseline to the FD. These improvements more than offset the significant decrease in statistics in the FD. They are the first limits to be determined for the neutrino sector in which LV and CPTV are assumed to be a perturbation on the conventional neutrino mass oscillations.

We gratefully acknowledge the many valuable conversations with Alan Kostelecký and Jorge Diaz during the course of this work. This work was supported by the U.S. DOE, the United Kingdom STFC, the U.S. 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.

*Deceased.


