Physics Letters B 718 (2013) 1303–1308

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Test of Lorentz and CPT violation with short baseline neutrino oscillation excesses

MiniBooNE Collaboration

A.A. Aguilar-Arevalo[n], C.E. Anderson[s], A.O. Bazarko[p], S.J. Brice[h], B.C. Brown[h], L. Bugel[m], J. Cao[o],
L. Coney[f,1], J.M. Conrad[m], D.C. Cox[j], A. Curioni[s], R. Dharmapalan[a], Z. Djurcic[b], D.A. Finley[h],
B.T. Fleming[s], R. Ford[h], F.G. Garcia[h], G.T. Garvey[k], J. Grange[i], C. Green[h,k], J.A. Green[j,k], T.L. Hart[e],
E. Hawker[d,k], W. Huelsnitz[k], R. Imlay[l], R.A. Johnson[d], G. Karagiorgi[m], P. Kasper[h], T. Katori[j,m,*,2],
T. Kobilarcik[h], I. Kourbanis[h], S. Koutsoliotas[c], E.M. Laird[p], S.K. Linden[s], J.M. Link[r], Y. Liu[o], Y. Liu[a],
W.C. Louis[k], K.B.M. Mahn[f], W. Marsh[h], C. Mauger[k], V.T. McGary[m], G. McGregor[k], W. Metcalf[l],
P.D. Meyers[p], F. Mills[h], G.B. Mills[k], J. Monroe[f], C.D. Moore[h], J. Mousseau[i], R.H. Nelson[e], P. Nienaber[q],
J.A. Nowak[l], B. Osmanov[i], S. Ouedraogo[l], R.B. Patterson[p], Z. Pavlovic[k], D. Perevalov[a,h], C.C. Polly[h],
E. Prebys[h], J.L. Raaf[d], H. Ray[i], B.P. Roe[o], A.D. Russell[h], V. Sandberg[k], R. Schirato[k], D. Schmitz[h],
M.H. Shaevitz[f], F.C. Shoemaker[p,3], D. Smith[g], M. Soderberg[s], M. Sorel[f,4], P. Spentzouris[h], J. Spitz[s],
I. Stancu[a], R.J. Stefanski[h], M. Sung[l], H.A. Tanaka[p], R. Tayloe[j], M. Tzanov[l], R.G. Van de Water[k],
M.O. Wascko[l,5], D.H. White[k], M.J. Wilking[e], H.J. Yang[o], G.P. Zeller[h], E.D. Zimmerman[e]

[a] *University of Alabama, Tuscaloosa, AL 35487, USA*
[b] *Argonne National Laboratory, Argonne, IL 60439, USA*
[c] *Bucknell University, Lewisburg, PA 17837, USA*
[d] *University of Cincinnati, Cincinnati, OH 45221, USA*
[e] *University of Colorado, Boulder, CO 80309, USA*
[f] *Columbia University, New York, NY 10027, USA*
[g] *Embry Riddle Aeronautical University, Prescott, AZ 86301, USA*
[h] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[i] *University of Florida, Gainesville, FL 32611, USA*
[j] *Indiana University, Bloomington, IN 47405, USA*
[k] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[l] *Louisiana State University, Baton Rouge, LA 70803, USA*
[m] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[n] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. 04510, Mexico*
[o] *University of Michigan, Ann Arbor, MI 48109, USA*
[p] *Princeton University, Princeton, NJ 08544, USA*
[q] *Saint Mary's University of Minnesota, Winona, MN 55987, USA*
[r] *Virginia Polytechnic Institute & State University, Blacksburg, VA 24061, USA*
[s] *Yale University, New Haven, CT 06520, USA*

ARTICLE INFO

Article history:
Received 26 August 2012
Received in revised form 6 November 2012
Accepted 8 December 2012
Available online 10 December 2012
Editor: T. Yanagida

Keywords:
MiniBooNE

ABSTRACT

The sidereal time dependence of MiniBooNE ν_e and $\bar{\nu}_e$ appearance data is analyzed to search for evidence of Lorentz and CPT violation. An unbinned Kolmogorov–Smirnov (K–S) test shows both the ν_e and $\bar{\nu}_e$ appearance data are compatible with the null sidereal variation hypothesis to more than 5%. Using an unbinned likelihood fit with a Lorentz-violating oscillation model derived from the Standard Model Extension (SME) to describe any excess events over background, we find that the ν_e appearance data prefer a sidereal time-independent solution, and the $\bar{\nu}_e$ appearance data slightly prefer a sidereal time-dependent solution. Limits of order 10^{-20} GeV are placed on combinations of SME coefficients. These

---

[*] Corresponding author at: Massachusetts Institute of Technology, Cambridge, MA 02139, USA. Tel.: +1 630 840 4759; fax: +1 630 840 6520.
E-mail address: katori@fnal.gov (T. Katori).

http://dx.doi.org/10.1016/j.physletb.2012.12.020

Neutrino oscillation
Lorentz violation

limits give the best limits on certain SME coefficients for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. The fit values and limits of combinations of SME coefficients are provided.

1. Introduction to Lorentz violation

Violation of Lorentz invariance and CPT symmetry is a predicted phenomenon of Planck-scale physics, especially with a spontaneous violation [1], and it does not require any modifications in quantum field theory or general relativity. Since neutrino oscillation experiments are natural interferometers, they can serve as sensitive probes of spacetime structure. Thus, neutrino oscillations have the potential to provide the first experimental evidence for Lorentz and CPT violation through evidence of oscillations that deviate from the standard L/E dependence [2], or that show sidereal time-dependent oscillations as a consequence of a preferred direction in the universe [3].

In this Letter, we test the MiniBooNE $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation data [4,5] for the presence of a Lorentz violation signal. Similar analyses have been performed in other oscillation experiments, including LSND [6], MINOS [7], and IceCube [8]. Naively, experiments with longer baselines and higher energy neutrinos would be expected to have better sensitivity to Lorentz violation because small Lorentz-violating terms are more prominent at high energy, where neutrino mass terms are negligible. However, some Lorentz-violating neutrino oscillation models mimic the standard massive neutrino oscillation energy dependence [9]. Then, in this case, the signal may only be seen in sidereal variations of oscillation experiments.

2. MiniBooNE experiment

MiniBooNE is a ν_e ($\bar{\nu}_e$) appearance short baseline neutrino oscillation experiment at Fermilab. Neutrinos are created by the Booster Neutrino Beamline (BNB), which produces a 93% (83%) pure ν_μ ($\bar{\nu}_\mu$) beam in neutrino (anti-neutrino) mode, determined by the polarity of the magnetic focusing horn. The MiniBooNE Cherenkov detector, a 12.2 m diameter sphere filled with mineral oil, is used to detect charged particles from neutrino interactions and is located 541 m from the neutrino production target. It is equipped with 1280 8 inch PMTs in an optically separated inner volume and 240 8 inch veto PMTs in an outer veto region. Details of the detector and the BNB can be found elsewhere [10,11]. Charged leptons created by neutrino interactions in the detector produce Cherenkov photons, which are used to reconstruct charged particle tracks [12]. The measured angle and kinetic energy of the charged leptons are used to reconstruct the neutrino energy, E_ν^{QE}, for each event, under the assumption that the target nucleon is at rest inside the nucleus and the interaction type is charged current quasielastic (CCQE) [13].

For this analysis, we use the background and error estimates from [14] (neutrino mode) and [15] (anti-neutrino mode). For neutrino mode, data from 6.46×10^{20} protons on target (POT) are used. An excess in the "low-energy" region ($200 < E_\nu^{QE}(\mathrm{MeV}) < 475$) was observed, with 544 events reported as compared to the prediction, $409.8 \pm 23.3(\mathrm{stat.}) \pm 38.3(\mathrm{syst.})$. Interestingly, this excess does not show the expected L/E energy dependence of a simple two massive neutrino oscillation model. Additionally, it is not consistent with the energy region expected for the "LSND" signal [16]. For the anti-neutrino mode analysis (5.66×10^{20} POT), MiniBooNE observed a small excess in the low-energy region, and an excess in the region $475 < E_\nu^{QE}(\mathrm{MeV}) < 1300$. The excess in this "high-energy" region is found to be consistent with the LSND signal, assuming a two massive neutrino hypothesis, but remains statistically marginal. In the "combined" region ($200 < E_\nu^{QE}(\mathrm{MeV}) < 1300$), MiniBooNE observed 241 $\bar{\nu}_e$ candidate events as compared to the prediction, $200.7 \pm 15.5(\mathrm{stat.}) \pm 14.3(\mathrm{syst.})$.

Although the conflict between MiniBooNE neutrino and anti-neutrino mode results can be resolved in models without CPT violation [17], CPT violation is a viable option. Since CPT violation necessarily implies violation of Lorentz invariance within interactive quantum field theory [18], we are in a well-motivated position to search for Lorentz and CPT violation using the MiniBooNE data. In fact, proposed models motivated by Lorentz violation [19,20] can already accommodate world data including the MiniBooNE and LSND excesses with a small number of free parameters. Evidence for sidereal variation in the MiniBooNE excesses would provide a distinctive direct signal of Lorentz violation.

3. Analysis

We use the SME formalism for the general search for Lorentz violation [21]. The SME is an effective quantum field theory and the minimum extension of the Standard Model including particle Lorentz and CPT violation [21]. A variety of data have been analyzed under this formalism [22], including neutrino oscillations [6–8]. In the SME formalism for neutrinos, the evolution of a neutrino can be described by an effective Hamiltonian [3],

$$\left(h^\nu_{\mathrm{eff}}\right)_{ab} \sim \frac{1}{E}\left[(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu\right]_{ab}. \tag{1}$$

Here, E and p_μ are the energy and the four-momentum of a neutrino, and $(a_L)^\mu_{ab}$ and $(c_L)^{\mu\nu}_{ab}$ are CPT-odd and CPT-even SME coefficients in the flavor basis. Under the assumption that the baseline is short compared to the oscillation length [23], the $\nu_\mu \to \nu_e$ oscillation probability takes the form,

$$\begin{aligned} P \simeq \frac{L^2}{(\hbar c)^2}\big|&(\mathcal{C})_{e\mu} + (\mathcal{A}_s)_{e\mu}\sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{e\mu}\cos\omega_\oplus T_\oplus \\ &+ (\mathcal{B}_s)_{e\mu}\sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{e\mu}\cos 2\omega_\oplus T_\oplus\big|^2. \end{aligned} \tag{2}$$

This probability is a function of sidereal time, $T_\oplus$. Four parameters $(\mathcal{A}_s)_{e\mu}$, $(\mathcal{A}_c)_{e\mu}$, $(\mathcal{B}_s)_{e\mu}$, and $(\mathcal{B}_c)_{e\mu}$ are sidereal time dependent, and $(\mathcal{C})_{e\mu}$ is a sidereal time-independent parameter. We use a baseline distance of $L = 522.6$ m, where the average pion decay length is subtracted from the distance between the neutrino production target and detector. And $\omega_\oplus$ is the sidereal time angular frequency described shortly. These parameters are expressed in terms of SME coefficients and directional factors [23]. The same formula describes the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probability by switching the signs of the CPT-odd SME coefficients. We neglect the standard neutrino mass term, $m^2_{e\mu}/E \ll 10^{-20}$ GeV, which is well below our sensitivity, discussed later.

For this analysis, we convert the standard GPS time stamp for each event to local solar time (period 86,400.0 s) and sidereal time (period 86,164.1 s). We then define the local solar time angular

---

[1] Present address: University of California, Riverside, CA 92521, USA.

[2] Postal address: Fermilab, MS309, PO Box 500, Batavia, IL 60510, USA.

[3] Deceased.

[4] Present address: IFIC, Universidad de Valencia and CSIC, Valencia 46071, Spain.

[5] Present address: Imperial College, London SW7 2AZ, United Kingdom.