FERMILAB-Pub-02/001-T
hep-ph/0201xxx

Neutrinos that violate CPT, and the experiments that love them

G. Barenboim[a], **L. Borissov**[b], **J. Lykken**[a,c]

[a]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*
[b]*Columbia University, New York, NY, 10027, USA*
[c]*Enrico Fermi Institute, Univ. of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA*

Abstract

Recently we proposed a framework for explaining the observed evidence for neutrino oscillations without enlarging the neutrino sector, by introducing CPT violating Dirac masses for the neutrinos. In this paper we continue the exploration of the phenomenology of CPT violation in the neutrino sector. We show that our CPT violating model fits the existing SuperKamiokande data at least as well as the standard atmospheric neutrino oscillation models. We discuss the challenge of measuring CP violation in a neutrino sector that also violates CPT. We point out that the proposed off-axis extension of MINOS looks especially promising in this regard. Finally, we describe a method to compute CPT violating neutrino effects by mocking them up with analog matter effects.

1 Introduction

As discussed in [1] (see also [2]), CPT violation has the potential to explain all existing neutrino anomalies without either enlarging the neutrino sector or introducing other new degrees of freedom. The beauty and economy of this framework cannot escape the reader who recalls that sterile neutrinos where introduced into this game with the unique purpose of explaining all observed anomalies with oscillations. Furthermore, if CPT is violated by non-Standard Model dynamics, neutrinos are the most natural messengers of this breaking, which does not require a concomitant breaking of Lorentz invariance.

As in any model designed to include an explanation of the appearance signal observed in LSND, the most sonorous confirmation of our proposal will arise with the confirmation of LSND itself by MiniBooNE [3]. While this will not be enough in itself to claim that CPT is violated, the smoking gun of our model is that MiniBooNE will see an appearance signal only when running in the antineutrino mode and not in the neutrino one.

However, as we outlined in [1], this is by no means the unique way to get evidence of CPT violation in the neutrino sector. We can take a shortcut to the CPT violating path by combining the information of KamLAND [4] and Borexino [5] (see fig 1).

The Kamioka mine is now the home of KamLAND, an experiment whose principal goal is to confirm and pin down the mass difference involved in the solar neutrino oscillations (provided this mass difference lies in the large mixing angle (LMA) region), by studying the flux and energy spectra of neutrinos produced by Japanese commercial nuclear reactors. As the best fit point to all the neutrino experiments lies precisely in this region, there is a growing consensus that the LMA zone is definitely the right place to look. However, if CPT is violated, KamLAND might be exploring the right place (LMA solution for neutrinos) with the wrong tool (reactor neutrinos, *i.e.* , antineutrinos). According to our model, KamLAND will not see an oscillation signal, even if the mass difference involved in the solar neutrino oscillations lives in the LMA region. However, this evidence by itself will not be hailed as evidence of CPT violation. It will just drive the CPT conserving believers to regions in the parameter space that do not receive today the favor of the public, such as the LOW solution [6].

A confirmation of the fall of the last discrete symmetry might come nevertheless while combining this information with data from the Borexino experiment. Borexino is a solar neutrino real-time experiment at LNGS (Laboratori Nazionali del Gran Sasso) that makes use of the neutrino-electron scattering reaction to detect neutrinos emitted from the Sun. From the point of view of our CPT violating model, Borexino will explore the right place with the right tool. The experiment is mainly interested in the observation of the higher energy 7Be neutrinos, which produce a monochromatic line at 863 keV. This line is predicted by all the standard solar models to be the second most important neutrino production reaction (after the basic pp reaction) in the Sun. The flux of 7Be neutrinos is predicted much more accurately (with an uncertainty of less than 10%) and is about a 1000 times larger than the 8B neutrino flux that is measured by SuperKamiokande and SNO. Also, since 7Be decay produces only neutrino lines, the theoretical predictions of neutrino oscillations are more unique for 7Be than for the 8B neutrinos, which have a broad energy spectrum (0-15 MeV).

Borexino will see a signal inconsistent with background only if the solar neutrino solution involves a large mixing angle, *i.e.*, one of LMA, LOW, vacuum oscillations (VAC) or quasi-vacuum oscillations (QVO); for the small mixing angle (SMA) solution, the neutrino rate at Borexino will be suppressed almost down to the background level. Given a signal, Borexino can distinguish between different large mixing scenarios by looking at time variations, in particular seasonal and diurnal variations. The distinctive feature of a LOW solution will be earth matter effects which give diurnal variations, while the QVO and VAC regions both offer seasonal variations. Therefore, if Borexino does see a signal, and does not see either seasonal variation or day/night asymmetry, while KamLAND sees an oscillation signal, this will undoubtedly point towards a CPT violating spectrum with an LMA solution for the solar neutrinos. On the other hand, if either a seasonal or diurnal variation is observed at Borexino, we should wait till MiniBooNE closes the discussion about CPT in the LSND region (one way or the other).

At this point a word of caution is in order, as there exists a very small region (disfavored by the state of the art fits) where the LOW solution becomes the QVO one and in which no unmistakable signal can be observed. To completely rule out this particular point (which has a very low goodness of fit), the full capability of the near future experiments must be used, *i.e.* a day/night effect will be detected by KamLAND, after KamLAND is converted into a solar neutrino experiment.

2 Atmospheric vs (anti) atmospheric

Since SuperKamiokande (SK) is a water Cerenkov experiment it simply adds up all the neutrino and antineutrino information without distinction. One wonders then if there is any possibility of digging out from their data any hint about or constraint on the CPT violation in the atmospheric sector. With this goal in mind, we have performed a selective χ^2 fit to SK multi GeV and sub GeV data (a total of 40 data points), where

$$\chi^2_{\rm atm} = \sum_{M,S} \sum_{\alpha=e,\mu} \sum_{i=1}^{10} \frac{(R^{\rm exp}_{\alpha,i} - R^{\rm th}_{\alpha,i})^2}{\sigma^2_{\alpha i}} \quad . \tag{2.1}$$

Here $\sigma_{\alpha,i}$ are the statistical errors, the ratios $R_{\alpha,i}$ between the observed and predicted signal can be written as

$$R^{\rm exp}_{\alpha,i} = N^{\rm exp}_{\alpha,i} / N^{\rm MC}_{\alpha,i} \tag{2.2}$$

(with α indicating the lepton flavor and i counting the different bins, ten in total) and M, S stand for the multi-GeV and sub-GeV data respectively. As we have closely followed the spirit of the calculation in [10], we refer the reader to this article for details and skip the technicalities.

Since the parameter space is so huge (two mass differences, three mixing angles and one CP violating phase in each sector), we decided to make some simplifying assumptions which we believe will not have any impact on the results.

- All the CP violating phases have been set to zero.
- The mass difference related to LSND (the largest mass difference in the antineutrino sector) is fixed to some arbitrary value. For the energies and distances involved in the atmospheric neutrino experiment this mass difference corresponds to a rapid oscillation, and therefore its exact value is not relevant provided it is large enough.
- The mass difference involved in solar neutrino oscillations (the smaller in the neutrino sector) is fixed to its best-fit point in the LMA region, *i.e.* , $s^2_{12} = .29$ and $\Delta m^2_\odot = 4.5 \times 10^{-5}$ eV^2.

We are left therefore with seven parameters to fit: the neutrino and antineutrino mass differences giving the leading contribution to the atmospheric oscillations, $\Delta m^2_{\rm atm}$ and

$\Delta\bar{m}^2_{\rm atm}$ respectively, the corresponding mixing angles, the connecting angle in the neutrino sector s_{13}, and the remaining two angles in the antineutrino sector $\bar{s}_{23}$ and $\bar{s}_{13}$. For the sake of clarity Figure 2 provides a dictionary to our way of labeling the masses. As we label the masses from the bottom to the top, the lightest state always being m_1 (or $\bar{m}_1$), and the heaviest m_3 (or $\bar{m}_3$), the mass difference involved in atmospheric oscillations is Δm^2_{23} in the neutrino case (with mixing angle θ_{23}), while the one in the antineutrino channel is $\Delta\bar{m}^2_{12}$ (with an effective mixing angle $\sin(2\,\bar{\theta}_{\rm atm}) \simeq 4\bar{U}^2_{\mu 1}\bar{U}^2_{\mu 2}$). Remember that in the neutrino case Δm^2_{12} and θ_{12} drive the solar neutrino oscillations, while $\Delta\bar{m}^2_{23}$ and $\sin(2\,\theta_{LSND}) \simeq 4\bar{U}^2_{e3}\bar{U}^2_{\mu 3}$ will account for the LSND signal.

Let us remind the reader that the $\bar{s}_{13}$ angle is constrained by the CHOOZ experiment to be either close to zero or to one, as

$$\begin{aligned} P_{\rm CHOOZ} &= 1 - 4\bar{U}^2_{e3}(1-\bar{U}^2_{e3})\sin^2\left(\frac{\Delta m^2_{LSND}L}{4E}\right) - 4\bar{U}^2_{e1}\bar{U}^2_{e2}\sin^2\left(\frac{\Delta\bar{m}^2_{\rm atm}L}{4E}\right) \\ &\simeq 1 - 2\bar{s}^2_{13}\bar{c}^2_{13}\ , \end{aligned} \tag{2.3}$$

and in order to explain the LSND signal the latter solution will be needed. Summing up, we have seven parameters and 40 data points for which a scan over 100,000 points has found four regions with comparable goodness of fit and a χ^2 of about 39. One is centered at

$$s^2_{23} = .40 \quad , \quad s^2_{13} = .01 \quad , \quad \Delta m^2_{\rm atm} = 4\cdot 10^{-3}{\rm eV}^2 \tag{2.4}$$

for the neutrino spectrum and

$$\bar{s}^2_{12} = .74 \quad , \quad \bar{s}^2_{23} = .98 \quad , \quad \bar{s}^2_{13} = .90 \quad , \quad \Delta\bar{m}^2_{\rm atm} = 4\cdot 10^{-3}{\rm eV}^2$$

for the antineutrino spectrum, while the other three live around

$$s^2_{23} = .40 \quad , \quad s^2_{13} = .01 \quad , \quad \Delta m^2_{\rm atm} = (2.9, 2.6 \text{ and } 2.3)\cdot 10^{-3}{\rm eV}^2 \tag{2.5}$$

for the neutrino spectrum and

$$\bar{s}^2_{12} = .74 \quad , \quad \bar{s}^2_{23} = .98 \quad , \quad \bar{s}^2_{13} = .90 \quad , \quad \Delta\bar{m}^2_{\rm atm} = (5.8, 6.6 \text{ and } 7.6)\cdot 10^{-3}{\rm eV}^2$$

for the antineutrino spectrum respectively, which implies a χ^2/d.o.f $\simeq 1.2$. This should be compared with the result obtained (using the same program) for the CP conserving case of $\chi^2 = 48$ with $\chi^2/\text{d.o.f} \simeq 1.3$, where now the number of degrees of freedom is not 33 as before but 37, as only three parameters entered into the fit. In order to make a fair comparison we have fixed in both cases the solar parameters.

The "better" fit (in terms of a lower χ^2) of the CPT violating case is not surprising as more degrees of freedom are available and therefore better agreement with the data can be expected. However as both goodness of fit are similar the most we can say is that both schemes are equally good, at least from the SK point of view. As expected SK data are a better constraint for neutrinos than for antineutrinos as the combination of a lower cross section and a lower flux make the oscillation signal a predominantly neutrino one. Notwithstanding the above, a correlation between the mass differences was found as can be seen in Figure 3. For one of the best-fit regions both mass differences are almost equal, while for the other regions the neutrino mass difference is almost half (or one third of) the antineutrino one; the neutrino mass difference in this case coincides with the SK CPT conserving best-fit point. In all of our best-fit regions there is a large CPT violating difference in the mixing angles.

One should notice however that our best-fits points are wildly disfavored by CHOOZ, whose results were not taken into account in the fit. If one now imposes the CHOOZ bound, the best-fit regions remain approximately the same, but the χ^2 grows to values around 44. Nevertheless, the goodness of the fit, taken as $\chi^2/\text{d.o.f}$ becomes now approximately 1.3, and therefore is still as good as the CPT conserving case.

Our fit confirms the expectations of [11], but appears rather different from the findings of Ref [12]. Some difference from Ref [12] is expected since that work used a two generation approximation and didn't include matter effects. More interesting, Ref [12] allows the overall ν_μ/ν_e flux ratio to vary freely, a fact that has already proven to have a strong impact on the results. Specifically, in a CPT violating scenario varying this parameter pushes the fit to large values of $\Delta\bar{m}^2_{\text{atm}}$ ($\gtrsim 0.1 eV^2$), where the rapidly oscillating antineutrino contribution washes out, becoming essentially equivalent to a shift in the flux ratio. This possibility is best regarded as complementary to our results.

As a closing remark we would like to emphasize that ours was a coarse grain fit and would need improvement to compare with the state of the art for such analyses. The grid resolution on Figure 3 is $0.33 \times 10^{-3}\ eV^2$ with respect to $\Delta\bar{m}^2_{\text{atm}}$ and Δm^2_{atm}. While the shape and possibly even the number of minima may change with a finer resolution scan, we expect the overall correlation between the parameters evident from the figure to remain.

3 CP vs CPT

In a picture containing three oscillating Dirac neutrinos, a neutrino state of definite flavor α, owner of well defined weak interaction properties, is related to neutrino states of definite mass m_k by

$$\nu_\alpha = \sum_k U_{\alpha k} \nu_k \tag{3.1}$$

where U is the unitary mixing matrix which, for 3 families, depends on 3 mixing angles and 1 CP phase. It is clear that in the CPT conserving case, the mixing matrices in the neutrino and antineutrino sector are not independent, since one is the conjugated of the other. However, if CPT is no longer a good symmetry, both matrices are not related and an incredible rich experimental potential emerges. Let's then follow the game for awhile to see what are the smoking guns we are looking for.

If the "α" state is born at $t = 0$, the probability amplitude that, at time t, it will end up as the "β" state is

$$A(\alpha \to \beta; t) = \sum_k U_{\alpha k} U^*_{\beta k} exp[-iE_k t] \quad . \tag{3.2}$$

It can be seen from (3.2) that the time-dependent amplitude contains the interference of different "k" terms, with different weak phases in $U_{\alpha k}\, U^*_{\beta k}$ and different oscillation phases governed by E_k, precisely the necessary ingredients to generate CP violation in the oscillation probability. If we now impose CPT, the amplitude for conjugated flavor states satisfy

$$A(\bar{\alpha} \to \bar{\beta}; t) = \sum_k U^*_{\alpha k} U_{\beta k}\, exp[-iE_k t] \tag{3.3}$$

so that, CPT implies

$$A(\bar{\alpha} \to \bar{\beta}; t) = A^*(\alpha \to \beta; -t) \tag{3.4}$$

On the other hand, the CP transformation relates the probabilities for the original transition and its conjugate,

$$|A(\alpha \to \beta; t)|^2 = |A(\bar{\alpha} \to \bar{\beta}; t)|^2 \tag{3.5}$$

while the T invariance relates the probabilities for the original transition and its inverse

$$\begin{aligned} |A(\alpha \to \beta; t)|^2 &= |A(\beta \to \alpha; t)|^2 \\ |A(\bar{\alpha} \to \bar{\beta}; t)|^2 &= |A(\bar{\beta} \to \bar{\alpha}; t)|^2 \end{aligned} \tag{3.6}$$

Therefore, in a CPT conserving world, CP and T violation effects can take place in appearance experiments only. For disappearance experiments, $\beta = \alpha$, and Eq. (3.2) implies

$$A^*(\alpha \to \alpha; t) = A(\alpha \to \alpha; -t) \tag{3.7}$$

As a consequence, no CP or T violation effect can be manifested in reactor or solar neutrino experiments (in a CPT conserving scenario).

In a CPT violating scenario however, even the survival probabilities for the conjugated channels can be different, opening the door to a new world of measurements but closing the path to the possibility of measuring CP violation using conjugated channels. So far, most (if not all) the proposals of measuring the CP violating phase rely precisely on this technique, *i.e.* first assume CPT and then construct an asymmetry with the different channels. Therefore, if the physics which hides beyond the Standard Model does not conserve CPT, these asymmetries will confirm that neutrinos are antineutrinos have an independent spectra but will not provide any single clue to whether CP is violated. The question will be then, whether there is an experiment (besides the ones described in the previous section) able to not only test CPT by itself (not mixing results from different experiments) but also to measure genuine CP violation.

The answer is yes, such an experiment exists: it is MINOS [7]. It will search for neutrino oscillations and measure with unprecedent precision the muon neutrino survival probability. MINOS can run in neutrino and antineutrino modes; it will measure both survival probabilities and pin down the mass difference involved in the atmospheric neutrino signal in both channels independently with great accuracy, thus providing a self-consistent test of CPT. One should bear in mind that due to the difference in cross section and production, one ends up with approximately six more times neutrino than antineutrino signal, and therefore any CPT comparison must involve a sizeable amount of running time in the antineutrino mode. However this is independent of whether CPT is conserved or not, and has been already taken into account when planning to measure the CP phase by combining results from conjugated channels.

On top of that, the recent development of the off-axis beam ideas [9] (neutrinos emitted at angles 10-20 mrad with respect to the beam axis create an intense beam with well defined energy) provide the possibility of CP violating studies without resorting to conjugated channels. In this case the idea will be to measure in two detectors (Soudan mine and Lake Superior) the electron neutrino appearance probability and (with some knowledge of the connecting angle s_{13} or by just measuring the two values for the transition probability) extract the value of the CP phase. Remember that this angle is not constrained by reactor experiments (*e.g.* CHOOZ) as these experiments involve antineutrinos and therefore can be sizeable. The two detector proposal has the advantage that is not based on the assumption that CPT is conserved, and that (as it does not involve antineutrinos) more precision can be reached with less running time.

Apart from the man-made neutrinos, one can use directly the nature-made atmospheric neutrinos to check the status of the CPT symmetry. This is precisely the idea behind MONOLITH [8]. This experiment will compare the event rates induced by the near and far (downward and upward) atmospheric muon neutrino fluxes (exactly as SuperKamiokande does) but with an iron detector, and therefore will be able to constraint the neutrino and antineutrino mass differences independently.

All in all, although it is certainly against our prejudices, it is not entirely an anathema to propose that a breakdown of CPT invariance might be responsible for all the experimental evidence in the neutrino sector that has been found so far and cannot be explained within the Standard Model (or even its minimal extensions). Within this scheme, the mixing matrices U and $\bar{U}$ are unitary but not related to each other. The Kobayashi-Maskawa argument on the ambiguity in the phases of fermion fields reduces the number of independent real parameters to four each (the mixing angles plus one phase) for U and $\bar{U}$. Thus altogether there are 14 real parameters describing neutrino oscillations, three masses (two mass differences) and four mixing parameters for neutrinos and likewise for antineutrinos all of which can be determined in the forthcoming experiments. It is true that the obstacles in this task are high, but it is also true that the possible insight gained is even higher!

4 Resuscitating the ether

Although the CPT violating idea is tempting, it suffers from the drawback of being impractical for calculations. As any local Lorentz invariant field theory automatically conserves CPT, in order to discuss CPT violation, we must move to an operator Hamiltonian description in momentum space (as shown in [1]). Therefore by adopting CPT violation we have lost more than fifty years of developments in quantum field theory, and are back to square one for any calculational purpose. One might wonder then whether there is any possibility of keeping the utility of local field theory but not its restrictions, *i.e.* to have an effective field theory that mimics in some way CPT violation. In fact, this possibility does exist, and it has been known for quite a long time. Matter effects are the key to an effective field theory description of CPT violation.

When neutrinos propagate through matter, the forward scattering of neutrinos off the background matter will induce an index of refraction for the neutrinos (which is different from that of antineutrinos). The neutrino index of refraction will depend generally on the flavor (electron, muon and tau neutrinos will have different indices of refraction because the background matter contains different amounts of each of them). The index of refraction acts like an effective mass term. Thus the effects of CPT violation, for the purposes of calculation, can be modeled by a kind of "ether" populated by different concentrations of ether-matter, giving different effective masses for neutrinos and antineutrinos. For the sake of clarity, in the following we will illustrate our point using the passage of neutrinos through standard matter, *i.e.* matter composed only by electrons (no muons or taus). However the extension to matter containing heavy leptons is straightforward.

Background electrons in normal matter will interact via charged currents with electron neutrinos as

$$\mathcal{L}_{\rm cc} = \frac{G_F}{\sqrt{2}} \bar{e} \gamma^{\mu} \left(1-\gamma_5\right) \nu_e \;\; \bar{\nu}_e \gamma_{\mu} \left(1-\gamma_5\right) e \; , \tag{4.1}$$

which after a Fierz rearranging looks like

$$\mathcal{L}_{\text{cc}} = \frac{G_F}{\sqrt{2}} \bar{\nu}_e \gamma^\mu (1-\gamma_5)\, \nu_e \;\; \bar{e}\gamma_\mu (1-\gamma_5)\, e \; . \tag{4.2}$$

For a medium with electrons at rest, we have

$$\bar{e}\gamma_\mu (1-\gamma_5)\, e = \delta_{\mu 0} N_e \tag{4.3}$$

where N_e is the electron number density. This interaction is equivalent to a repulsive potential, $V = \sqrt{2} G_F N_e$, for left-handed neutrinos given by the wave function $\frac{1}{2}(1-\gamma_5)\, \nu_e$. For relativistic neutrinos, with $E \simeq p + m^2/2p$, this potential amounts to an effective mass for the electron neutrino

$$m^2_{\text{eff}} \equiv A = 2\sqrt{2} G_F N_e E. \tag{4.4}$$

In the flavor basis the potential is diagonal. Restricting ourselves to the two generation case for simplicity, the mass matrix becomes

$$M^2 = \left(U \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \right) \tag{4.5}$$

where U is the unitary transformation between the flavor and mass bases and A acts like an induced mass (squared) for the electron neutrino from the propagation through a background of electrons. The corresponding expressions in the antineutrino case can be obtained by the replacements, $A \longrightarrow -A$ and $U \longrightarrow U^*$.

M^2 can be diagonalized by U_m, the mixing matrix in the medium:

$$U_m^\dagger M^2 U_m \equiv \begin{pmatrix} M_1^2 & 0 \\ 0 & M_2^2 \end{pmatrix} \tag{4.6}$$

where

$$M^2_{2,1} = \frac{(\Sigma + A) \pm [(A - \Delta\text{cos}(2\theta))^2 + (\Delta\text{sin}(2\theta))^2]}{2} \tag{4.7}$$

with $\Sigma = m_2^2 + m_1^2$, $\Delta = m_2^2 - m_1^2$, θ is the mixing angle in vacuum and

$$U_m = \begin{pmatrix} \text{cos}\theta_m & -\text{sin}\theta_m \\ \text{sin}\theta_m & \text{cos}\theta_m \end{pmatrix} \tag{4.8}$$

where θ_m is the mixing angle in matter and is given by

$$\tan 2\theta_m = \frac{\Delta \sin(2\theta)}{-A + \Delta \cos(2\theta)} \ . \tag{4.9}$$

To make our point even more transparent, let us assume that $m_1 \simeq m_2 = m$. The neutrino masses in vacuum become

$$M_1^2 = m^2 + A \qquad M_2^2 = m^2 \tag{4.10}$$

while the antineutrino masses are given by

$$\bar{M}_1^2 = m^2 - A \qquad \bar{M}_2^2 = m^2 \ . \tag{4.11}$$

Even in this extremely simplified model a drastic breakdown of CPT can be obtained. The complete scheme, including the three families and effective densities for all the charged leptons, can accommodate a large subclass of CPT violating spectra (although no analytic formulae can be expected in this case).

It is clear then that in a typical medium such as the Earth or the Sun, neutrinos and antineutrinos have CPT violating spectra. Therefore, in order to describe the CPT violating extension of the Standard Model, and thus to account for all the existing neutrino anomalies which we have presented in [1], we have to only choose the electron (muon and tau) density that is appropriate to describe the CPT violating mass difference that we need. Calculation of physicial processes that we are interested in can then be performed with standard field theory techniques.

5 Conclusions

CPT violation has the potential to explain all the existing evidence about neutrinos with oscillations to active flavors. Such a scenario makes specific (and unique) predictions that will be tested in the present round of neutrino experiments. CPT violation can be searched for independently of whether it occurs in conjunction with CP violation or not. As we have shown, both symmetries can (and must) be tested separately. So far, we have no evidence of CPT conservation in the neutrino sector. Indeed as we have shown all the existing data, including from SuperKamiokande, is most economically explained if CPT is broken. The true status of CPT in the neutrino sector can be established by the combined results of KamLAND and Borexino, or by MiniBooNE. In the atmospheric sector MINOS is the ideal experiment for such a test.

From a practical point of view, all the calculational inconveniences of a CPT violating model can be avoided (for a large subclass of models) by constructing an analog effective theory of neutrinos propagating in a medium with a density such as to reproduce the desired mass pattern.

Certainly, there are many exciting features and potential signatures for models with CPT violation. We leave it to the reader to judge the degree of skepticism that is appropriate when considering the phenomenology of these theories, which disobey the eleventh commandment, *i.e.* thou shalt conserve CPT.

Acknowledgements

We are grateful to P. Mackenzie and J. Simone for sharing with us their lattice expertise and giving us access to their lattice cluster. We thank John Beacom, Nicole Bell, Janet Conrad, Andre de Gouvea, Boris Kayser and Solveig Skadhauge for comments and suggestions. Research by GB and JL was supported by the U.S. Department of Energy Grant DE-AC02-76CHO3000 while that of LB by the Sloan Foundation.

References

[1] G. Barenboim, L. Borissov, J. Lykken and A. Y. Smirnov, “Neutrinos as the messengers of CPT violation,” arXiv:hep-ph/0108199.

[2] H. Murayama and T. Yanagida, Phys. Lett. B **520**, 263 (2001) [arXiv:hep-ph/0010178].

[3] MiniBooNE Collaboration, A. Bazarki, Nucl. Phys. B 91 (Proc. Suppl.) (2000), 210.

[4] KamLAND Collaboration, A.Piepke, Nucl. Phys. B 91 (Proc. Suppl.) (2000), 99.

[5] The Borexino web page: almine.mi.infn.it/html/borexino.html.

[6] A. de Gouvea and C. Pena-Garay, Phys. Rev. D **64**, 113011 (2001) [arXiv:hep-ph/0107186].

[7] The MINOS Technical Design Report, Fermilab report NUMI-L-337.

[8] MONOLITH Collaboration, N.Y. Agafonova et al., “MONOLITH: a Massive magentized iron detector for neutrino oscillation studies”, LNGS-P26-2000, LNGS-P26-00, CERN-SPSC-2000-031, CERN-SPSC-M-657.

[9] K. T. McDonald, “An off-axis neutrino beam,” arXiv:hep-ex/0111033; A. Para and M. Szleper, “Neutrino oscillations experiments using off-axis NuMI beam,” arXiv:hep-ex/0110032.

[10] G. Barenboim, A. Dighe and S. Skadhauge, “Combining LSND and atmospheric anomalies in a three-neutrino picture,” arXiv:hep-ph/0106002.

[11] V. D. Barger, S. Pakvasa, T. J. Weiler and K. Whisnant, Phys. Rev. Lett. **85**, 5055 (2000) [arXiv:hep-ph/0005197].

[12] S. Skadhauge, “Probing CPT violation with atmospheric neutrinos,” arXiv:hep-ph/0112189.

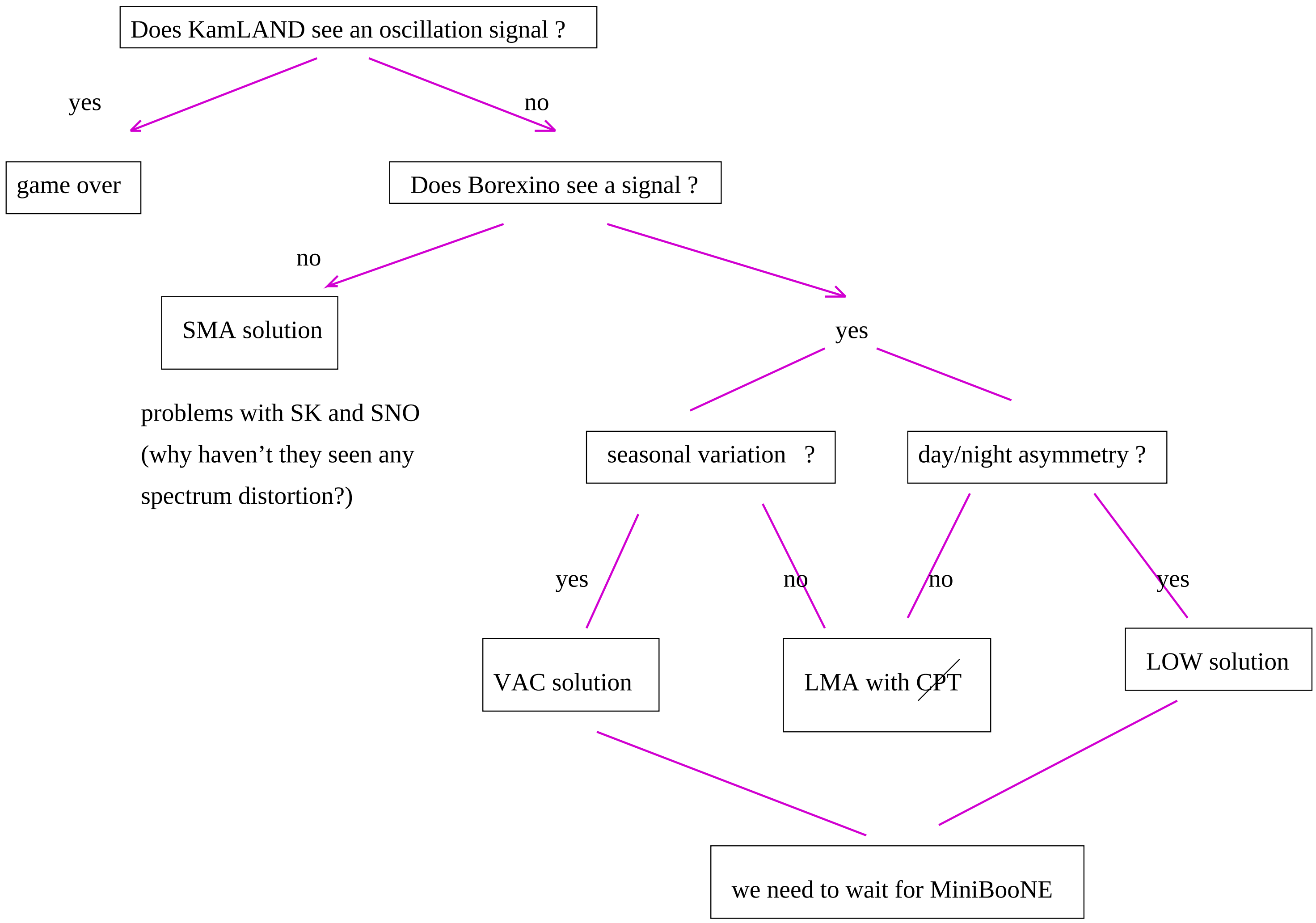

Figure 1: Flow chart for discovering CPT violation by combining the results of KamLAND and Borexino

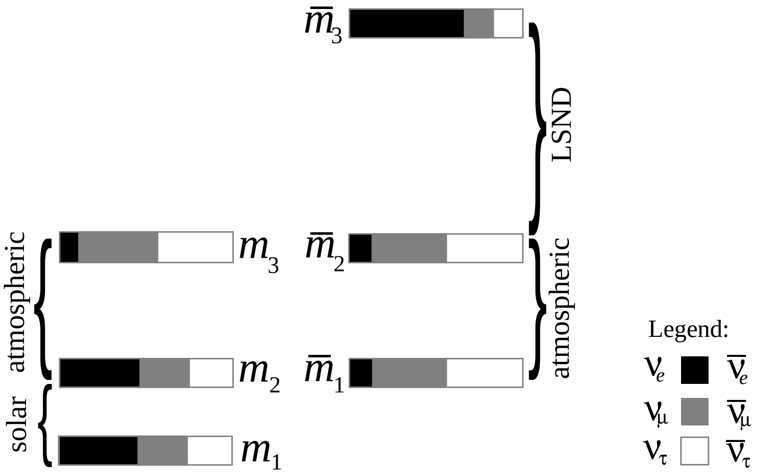

Figure 2: Typical CPT violating (hierarchical) spectrum, able to account for the LSND, atmospheric and solar neutrino evidence

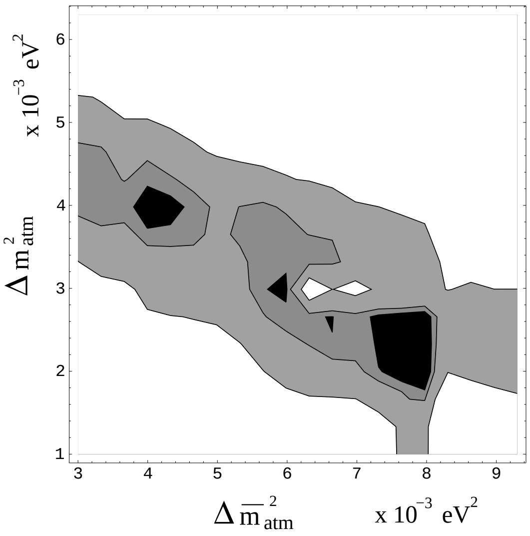

Figure 3: Best-fit regions for the SK atmospheric neutrino data in the $\Delta\bar{m}^2_{\rm atm}$ - $\Delta m^2_{\rm atm}$ plane. The allowed regions are shown at 90%, 95 % and 99% CL with respect to the global minimum.