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Neutrinos as the messengers of CPT violation

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Abstract

CPT violation has the potential to explain all three existing neutrino anomalies without enlarging the neutrino sector. CPT violation in the Dirac mass terms of the three neutrino flavors preserves Lorentz invariance, but generates independent masses for neutrinos and antineutrinos. This specific signature is strongly motivated by braneworld scenarios with extra dimensions, where neutrinos are the natural messengers for Standard Model physics of CPT violation in the bulk. A simple model of maximal CPT violation is sufficient to explain the exisiting neutrino data quite neatly, while making dramatic predictions for the upcoming KamLAND and MiniBooNE experiments. Furthermore we obtain a promising new mechanism for baryogenesis.

1 Introduction

With the final results by the LSND Collaboration [1] consistently indicating evidence of $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations with a large frequency, we are faced with the fact that the simplest extensions of the Standard Model cannot accommodate the observed experimental anomalies in the neutrino sector. With three species of neutrinos only two independent mass differences can be chosen, and only two of the observed "anomalies" (LSND, atmospheric, and solar) can be explained via oscillations.

There have traditionally been two ways out of this predicament: (i) turn a blind eye to the LSND experiment and keep our fingers crossed that it will be contradicted by future experiments such as MiniBooNE, or (ii) introduce additional neutrino species (sterile neutrino) and achieve this way the needed third mass difference. However sterile neutrino scenarios were recently dealt a blow by the dramatic first results from the SNO experiment [3]. While SNO does not rule out a non-active neutrino component [4], it certainly makes it harder to reconcile a sterile neutrino which makes the LSND anomaly possible yet hides so efficiently in the solar and atmospheric neutrino data.

Another theoretical approach to neutrino anomalies is to introduce new physics into the neutrino sector, rather than enlarging it. For example new flavor-changing neutrino interactions [2] work well to explain the solar data. However one should keep in mind that these solutions also fix one of the mass difference degrees of freedom, and thus do not directly address our basic predicament. Similar statements apply to schemes which postulate violations of Lorentz invariance or the Equivalence Principle [5]. It should also be stressed that new physics solutions for the LSND case are even harder to find. In particular many new physics signals capable of explaining LSND (e.g. exotic decays of muons) should also have been seen by the KARMEN experiment.

In this letter we point out that CPT violation has the potential to explain all three existing neutrino anomalies without enlarging the neutrino sector. CPT violation in the Dirac mass terms of the three neutrino flavors preserves Lorentz invariance, but generates independent masses for neutrinos and antineutrinos. This additional freedom, as we shall see, is sufficient to explain the exisiting neutrino data quite neatly, while making dramatic predictions for the upcoming KamLAND and MiniBooNE experiments. Furthermore we obtain a promising new mechanism for baryogenesis.

The idea that Lorentz invariant CPT violation could be observable in the neutrino sector was first suggested by Barger *et al.* [6]. More recently, Murayama and Yanagida suggested that CPT violating neutrino-antineutrino mass differences could explain a possible discrepancy between LSND results and neutrinos observed from supernova 1987a [7]. They also observed that CPT violation has the potential to explain all three existing neutrino anomalies without introducing a sterile neutrino.

2 CPT violation in the neutrino sector

Our starting point is the hypothesis that the largest contributions to neutrino masses are CPT violating Dirac mass terms. If CPT were conserved, Dirac masses would arise from local Yukawa type interactions of fields. These interactions would involve the Standard Model left-handed neutrino complex Weyl spinor fields $\nu_{iL}(t,\mathbf{x})$, where i=1, 2, 3 labels the three neutrino species in the mass eigenstate basis. We would also need the Standard Model complex Higgs field $\phi(t,\mathbf{x})$, with $\langle\phi\rangle = v = 174$ GeV denoting the vacuum expectation value that breaks electroweak symmetry and gives mass to the charged fermions. We suppress the $SU(2)_L$ index structure. In addition, Dirac mass terms for neutrinos require that we introduce right-handed $SU(2)_L$ singlet complex Weyl neutrino fields $N_i(t,\mathbf{x})$.

Any local field theory interaction that is Lorentz invariant will automatically conserve CPT, so in order to discuss CPT violation we must go to an operator hamiltonian description in momentum space. Suppressing flavor indices, we can write standard operator expansions for the static neutrino fields:

$$\psi(\mathbf{x}) = \begin{pmatrix} \nu_L(\mathbf{x}) \\ N(\mathbf{x}) \end{pmatrix} = \frac{1}{\sqrt{2}} \int \frac{d^3p}{(2\pi)^3} \sum_s \left(a^s_{\mathbf{p}} u^s(\mathbf{p}) \mathrm{e}^{i\mathbf{p}\cdot\mathbf{x}} + b^{s\dagger}_{\mathbf{p}} v^s(\mathbf{p}) \mathrm{e}^{-i\mathbf{p}\cdot\mathbf{x}} \right) \tag{2.1}$$

$$\bar{\psi}(\mathbf{x}) = \frac{1}{\sqrt{2}} \int \frac{d^3p}{(2\pi)^3} \sum_s \left(b^s_{\mathbf{p}} \bar{v}^s(\mathbf{p}) \mathrm{e}^{i\mathbf{p}\cdot\mathbf{x}} + a^{s\dagger}_{\mathbf{p}} \bar{u}^s(\mathbf{p}) \mathrm{e}^{-i\mathbf{p}\cdot\mathbf{x}} \right) \tag{2.2}$$

Here $u^s(\mathbf{p})$ and $v^s(\mathbf{p})$, s=1, 2, form an orthogonal on-shell spinor basis, while $a^s_{\mathbf{p}}$ and $b^s_{\mathbf{p}}$ are anticommuting Fock space operators:

$$\{a^r_{\mathbf{p}}, a^{s\dagger}_{\mathbf{p}'}\} = \{b^r_{\mathbf{p}}, b^{s\dagger}_{\mathbf{p}'}\} = \frac{1}{E_{\mathbf{p}}} (2\pi)^3 \delta^{(3)}(\mathbf{p} - \mathbf{p}') \delta^{rs} \tag{2.3}$$

In the massless limit, $a_{\mathbf{p}}^{1\dagger}$, $a_{\mathbf{p}}^{2\dagger}$ create the neutrino components of ν_L and N, while $b_{\mathbf{p}}^{1\dagger}$, $b_{\mathbf{p}}^{2\dagger}$ create the antineutrino components.

The free part of the Hamiltonian is diagonalized by our use of an orthogonal on-shell spinor basis:

$$\begin{aligned} H_0 \quad &= \int d^3x \, \bar{\psi}(\mathbf{x}) \left[-i\vec{\gamma}\cdot\vec{\nabla} + m\right] \psi(\mathbf{x}) \\ &= \int \tfrac{d^3p}{(2\pi)^3} \, (\mathbf{p}^2 + m^2) \textstyle\sum_s \left[a_{\mathbf{p}}^{s\dagger} a_{\mathbf{p}}^{s} + b_{\mathbf{p}}^{s\dagger} b_{\mathbf{p}}^{s}\right] \end{aligned} \tag{2.4}$$

A CPT transformation interchanges the neutrino Fock operators $a_{\mathbf{p}}^{s}$ with the antineutrino Fock operators $b_{\mathbf{p}}^{s}$. Thus CPT invariance implies that neutrinos and antineutrinos have the same mass. Conversely, we can break CPT by introducing independent mass terms for neutrinos and antineutrinos:

$$H_0 = \int \frac{d^3p}{(2\pi)^3} \, \sum_s \left[(\mathbf{p}^2 + m^2) a_{\mathbf{p}}^{s\dagger} a_{\mathbf{p}}^{s} + (\mathbf{p}^2 + \bar{m}^2) b_{\mathbf{p}}^{s\dagger} b_{\mathbf{p}}^{s}\right] \tag{2.5}$$

For $m \neq \bar{m}$ this hamiltonian violates CPT. It cannot be derived from any local field interaction, since there is no way to find an orthogonal spinor basis when the $u^s(\mathbf{p})$ and $v^s(\mathbf{p})$ spinors would have to obey on-shell conditions with different masses. As a result, this CPT violating but Lorentz invariant extension of the Standard Model is nonlocal, *i.e.*, in position space some neutrino anticommutators will be nonvanishing for spacelike separations. Although non locality may seem pathological, the only obvious measurement that detects this pathology is the measurement of the neutrino and antineutrino masses through oscillations.

Restoring the flavor indices, we can parametrize the observable effects of CPT violation by three real parameters[1] $\tan\beta_i$, $i = 1, 2, 3$:

$$m = \tan\beta \; \bar{m} \quad . \tag{2.6}$$

For $\tan\beta=0$, only the antineutrino gets mass, while for $\cot\beta=0$ only the neutrino gets mass. We will refer to either of these two limiting cases as "maximal" CPT violation. For $\tan\beta=\pm 1$, CPT is restored.

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[1] In addition to $\tan\beta_i$, we will in general need four more parameters (three angles and a phase) to transform the neutrino mass eigenstate basis into the antineutrino mass eigenstate basis.

Maximal CPT violation is sufficient to obtain the attractive neutrino mass spectrum shown in Fig. 1, which accounts for the LSND, atmospheric, and solar neutrino data using only three species of neutrinos. In this simple toy model, two antineutrinos, together with one neutrino, receive CPT violating Dirac masses. The remaining two neutrinos, as well as the antineutrino, do not receive Dirac masses, but can generically pick up small masses from higher order effects, *i.e.*, CPT invariant higher dimension operators like

$$\nu_L^T \sigma_2 \nu_L \cdot \phi^* \phi \quad , \tag{2.7}$$

where again we have suppressed the $SU(2)_L$ index structure.

In the figure, the $\bar{\nu}_\mu$ to $\bar{\nu}_e$ transitions observed by LSND are explained by the large CPT violating (dominantly) electron antineutrino mass. The solar oscillations are the result of the much smaller CPT conserving mass splittings between ν_2 and ν_1. Atmospheric oscillations are assumed to be ν_μ–ν_τ. In the figure, the ν_2–ν_3 mass-squared splitting has approximately the same magnitude, as the $\bar{\nu}_1$–$\bar{\nu}_2$ splitting. As a result atmospheric muon neutrinos and antineutrinos will have similar oscillation lengths, in accord with the data from SuperKamiokande. Being a water Cerenkov detector, SuperK does not distinguish neutrinos from antineutrinos, and washes out any possible difference in the frequencies of the different channels.

Of course Fig. 1 is just an example: both spectra are pretty much free and can be accommodated in many different ways; e.g. one can have inverted spectrum while the other has normal hierarchy, both can be inverted, etc. Our approach is agnostic about the mixing matrix.

3 Mechanisms for CPT violation

CPT is automatically conserved in a local relativistic quantum field theory. Possible violations of CPT have traditionally been studied in tandem with violations of Lorentz invariance [8], with the assumption that CPT breaking is communicated to all/most sectors of the Standard Model. In this case the upper bound on the neutral kaon mass difference provides an extremely stringent bound on CPT violation.

Theoretical motivation for CPT violation usually starts with string theory, since string theory is not a quantum field theory. In weakly coupled limits of string theory the low

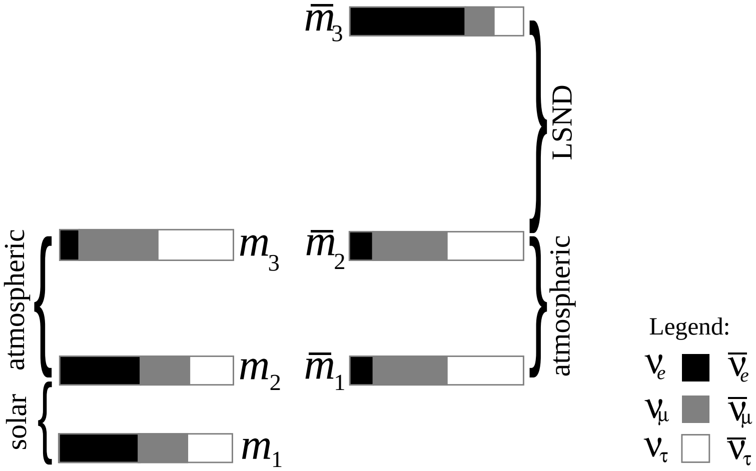

Figure 1: *Possible neutrino mass spectrum in the case of maximal CPT violation. Although the figure shows an example of large mixing, our approach is agnostic about the mixing matrix.*

energy effective field theory will inherit CPT invariance from the CPT symmetry of the underlying worldsheet dynamics. However it has been suggested that nonperturbative string effects may violate CPT directly, and it is also plausible that the choice of string vacuum may violate CPT spontaneously in the low energy four dimensional effective field theory [9].

We now observe that, in braneworld models of string phenomenology, the neutrino sector is the most likely messenger of CPT violation to the rest of the Standard Model. This is because the source of dynamical or spontaneous CPT violation will lie in the bulk, and the Standard Model effects will only be visible via couplings of Standard Model fields (assumed to reside on branes) to suitable bulk messengers. The generic candidates for the bulk fields which act as the messengers of CPT are (i) gravity and (ii) the right-handed neutrinos (*i.e.*, the $SU(2)_L$ singlet neutrinos N_i). If the extra dimensions are not large enough, gravity effects are difficult to observe, while the right-handed neutrinos can still have easily observable Dirac mass couplings. These are precisely the braneworld scenarios where the effects of Kaluza-Klein sterile neutrinos are negligible for neutrino oscillation physics.

Having argued that neutrinos are the likely messengers of CPT violation in a huge class of string models, we may evade all of the stringent bounds on Standard Model CPT violation from the kaon sector or any other sector. We may also remain agnostic on the bulk source of CPT violation, provided that we are convinced that plausible sources exist.

In this respect it is encouraging to examine a potential simple mechanism. In realistic braneworld models the Standard Model often resides on a collection of branes in a higher dimensional spacetime background which is an orbifold or orientifold. The orbifold background generically breaks symmetries of the low energy four dimensional effective description of the Standard Model sector. The broken symmetries can include spacetime symmetries, *e.g.*, supersymmetry. Scherk-Schwarz type breaking of symmetries can also occur in such backgrounds. Thus it is natural to speculate that a suitably contrived orbifolding can lead to apparent CPT violation in the four dimensional effective theory.

More generally, suppose that (by whatever mechanism) some neutral bulk fermion acquires a CPT violating Dirac mass of the type described in the previous section. We can then turn on a brane-bulk Yukawa coupling between the Standard Model ν_L, ϕ, and half of the components of this bulk fermion. Upon rediagonalization this will communicate the bulk CPT violation to the observable neutrino spectrum.

4 Equilibrium baryogenesis

During the electroweak phase transition in the early universe, leptons acquire masses from electroweak symmetry breaking. A mass difference between neutrinos and antineutrinos would create a difference in the chemical potential for populating neutrino and antineutrino states, resulting in a lepton matter-antimatter asymmetry proportional to the mass difference. This asymmetry is mediated to the baryon sector through sphaleron processes which violate $B + L$ with great efficiency.

If we assume that the electron antineutrinos are about 1 eV heavier than the neutrinos (as needed to explain the LSND signal) then the resulting chemical potential between ν_1 and $\bar{\nu}_1$ is of the order of 1 eV. In thermal equilibrium, this will result in a baryon asymmetry given by [10]

$$n_B = n_\nu - n_{\bar{\nu}} \simeq \frac{\mu_\nu T^2}{6} \tag{4.1}$$

which at the electroweak symmetry breaking scale of 100 GeV gives $\frac{n_B}{s} \sim \frac{\mu_\nu}{T} \sim 10^{-11}$. in rough agreement with the observed value. This mechanism does not need CP violation and is produced in equilibrium.

5 Predictions and discussion

This CPT violating scenario, with different mass spectra for neutrinos and antineutrinos, will have dramatic signatures in future neutrino oscillation experiments. The most striking consequence will be seen in MiniBooNE (scheduled to start taking data in 2002), which is meant to close the discussion about LSND one way or the other. According to our picture, MiniBooNE will be able to confirm LSND only when running in the antineutrino mode[2]. Although their original intention was to run primarily in neutrino mode, the other possibility is under consideration [11]. In addition, within this scheme, oscillations of electron neutrinos driven by $\Delta m^2_{\rm atm}$ are different in neutrino and antineutrino channels. In the latter, these oscillations are strongly suppressed, whereas in the neutrino channel they can be at the level of the present upper bound. It is important to notice that in this case the BUGEY bound is irrelevant and large effects can be expected.

Before that, the KamLAND detector [12], located inside a mine in Japan and sensitive only to electron antineutrinos, will not see an oscillation signal even if the solar neutrinos have a LMA oscillation pattern. This signature, as well as the MiniBooNE one, is independent of whether one has the maximal CPT violating scenario.

Regarding atmospheric neutrinos, all the experiments aimed to measure the atmospheric mass differences with high precision will find that this magnitude is intimately related to the channel they are exploring, (possibly) discovering slightly different values for CPT conjugated channels and even opposite signs. Current experiments, such as SuperK, do not distinguish neutrinos from antineutrinos allowing the atmospheric mass difference to be not necessarily the same in the neutrino and antineutrino channels. Pre-

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[2] This point was noted already in Ref. [7].

dictions in this case are not independent of the realization of CPT violation (i.e, maximal or not).

The observation of a neutrino burst from the next supernova can also provide a useful tool to constrain separately both the neutrino and the antineutrino spectra [7].

This scenario, having a Dirac electron antineutrino mass of $\mathcal{O}(1)$ eV, will be explored in the next generation of beta-decay endpoint searches such as the proposed KATRIN experiment, featuring a large tritium spectrometer with sub-eV sensitivity [13].

6 Conclusions

The general class of models presented here demonstrate that just three neutrino flavors with CPT violation can account for all neutrino anomalies with oscillations. These CPT violating models, which may arise naturally in string theory and brane world scenarios, make very specific benchmark predictions that will be tested in the near future. An evidence for violation of the CPT symmetry would undoubtedly point towards more than three spatial dimensions, and will provide an alternative to Kaluza-Klein mode searches for testing extra dimensions.

CPT violation, which contrary to CP or T violation, can be also seen in disappearance experiments , puts a serious bias on CP violation measurements which combine results for conjugated channels. In that case CP violation is a subdominant effect while the main effect is CPT violation. In order to measure genuine CP violation, at least two detectors for each channel are needed.

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