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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 on-shell 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 existing neutrino data quite neatly, while making dramatic predictions for the KamLAND and MiniBooNE experiments. We obtain a promising and economical new mechanism for electroweak baryogenesis.

Keywords: Discrete and Finite Symmetries, Neutrino Physics.

Contents

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.

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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 electroweak 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 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 fields $\nu_{iL}(t,\mathbf{x})$, where i labels the three neutrino species in the mass eigenstate basis, and we suppress the $\mathrm{SU}(2)_L$ index structure. In addition, Dirac mass terms for neutrinos require that we introduce right-handed $\mathrm{SU}(2)_L$ singlet 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 in terms of an orthogonal on-shell spinor basis, and anticommuting Fock space operators $a^s_{\mathbf{p}}$ and $b^s_{\mathbf{p}}$:

$$\left\{a^r_{\mathbf{p}}, a^{s\dagger}_{\mathbf{p}'}\right\} = \left\{b^r_{\mathbf{p}}, b^{s\dagger}_{\mathbf{p}'}\right\} = (2\pi)^3\delta^{(3)}\left(\mathbf{p}-\mathbf{p}'\right)\delta^{rs}\,. \tag{2.1}$$

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

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

$$H_0 = \int \frac{d^3p}{(2\pi)^3}\, E_{\mathbf{p}} \sum_s \left[a^{s\dagger}_{\mathbf{p}} a^s_{\mathbf{p}} + b^{s\dagger}_{\mathbf{p}} b^s_{\mathbf{p}}\right]. \tag{2.2}$$

A CPT transformation interchanges the neutrino Fock operators $a^s_{\mathbf{p}}$ with the antineutrino Fock operators $b^s_{\mathbf{p}}$. 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:

$$H_0 = \int \frac{d^3p}{(2\pi)^3} \sum_s \left[\sqrt{\mathbf{p}^2+m^2}\, a^{s\dagger}_{\mathbf{p}} a^s_{\mathbf{p}} + \sqrt{\mathbf{p}^2+\bar{m}^2}\, b^{s\dagger}_{\mathbf{p}} b^s_{\mathbf{p}}\right]. \tag{2.3}$$

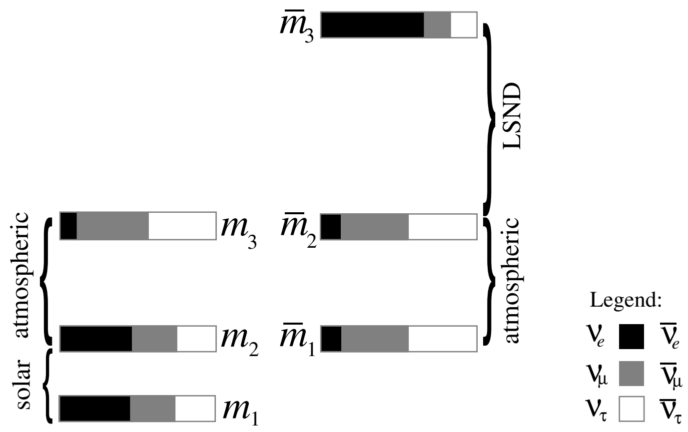

Figure 1: Possible neutrino mass spectrum in the case of maximal CPT violation. Although the figure shows an example of large mixing, our approach is agnostic about the mixing matrix.

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 extension of the Standard Model is Lorentz invariant (on-shell) but nonlocal, i.e. in position space some neutrino anticommutators will be nonvanishing for spacelike separations. Although nonlocality 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 $\tan\beta_i$: $m = \bar{m}\tan\beta$. 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. In addition to the $\tan\beta_i$, we would 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 figure 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 dimension CPT invariant operators.

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 $\nu_\mu - \nu_\tau$. In the figure, the $\nu_2 - \nu_3$ 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

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from SuperKamiokande. Being a water Cerenkov detector, SuperK does not distinguish neutrinos from antineutrinos, tending to wash out any difference in the frequencies of the different channels.

Of course figure 1 is just an example: both spectra are pretty much free and can be accommodated in many different ways. 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.

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 $\mathrm{SU}(2)_L$ 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 brane models, we may evade all of the stringent bounds on Standard Model CPT violation from the kaon sector or any other sector. Standard Model processes outside the neutrino sector will exhibit CPT violation due to loop effects from neutrinos, but these are enormously suppressed by factors of G_F times the CPT violating neutrino masses squared. We may also remain agnostic on the bulk source of CPT violation, provided that we are convinced that plausible sources exist.

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

4. CPT and baryogenesis

Our model of CPT violating Dirac neutrino masses provides a novel and extremely economical mechanism to generate the observed baryon asymmetry, through a process of equilibrium electroweak baryogenesis. Our mechanism works in thermal equilibrium, without CP violation, and requires only sphalerons as the source of B and L violation.

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As observed long ago by Dolgov and Zeldovich [10], CPT violation has the attractive feature that it obviates the need for two of the three Sakharov conditions, namely the requirements of out-of-equilibrium and CP violating processes. Indeed they observed that if B is violated, and if baryons have CPT violating masses, then kinematics induces a baryon asymmetry. For a single species of fermion with CPT violating masses $m \neq \bar{m}$, the net fermion number per unit volume, $\langle N - \bar{N} \rangle$, can be written

$$\langle N - \bar{N} \rangle = T^3 [I_0(m) - I_0(\bar{m})] \,, \tag{4.1}$$

where $I_0(m)$ is a dimensionless Fermi-Dirac integral. At high temperatures the resulting asymmetry is of order $\beta \left(m^2 - \bar{m}^2 \right)$. To generate the desired baryon asymmetry through equilibrium processes at the electroweak scale, this would require CPT violating mass differences on the order of an MeV. At any rate we show below that the Dolgov-Zeldovich mechanism does not generate an asymmetry if sphalerons are the source of B violation.

Sphaleron transitions are topologically nontrivial fluctuations of the electroweak gauge fields and Higgs field. Sphaleron transitions violate $B + L$ through the phenomenon of level crossing [11]. For a massless Dirac fermion with electroweak quantum numbers, the spectrum of the covariant Dirac operator is deformed by the sphaleron field configuration. As the sphaleron transition proceeds, filled negative frequency eigenstates of the Dirac operator can be deformed to filled positive frequency states (or vice-versa); this level crossing can result in a net change ± 1 (per species) in fermion number. This is seen explicitly as the existence of a single normalizable zero energy mode of the Dirac operator in the presence of the sphaleron fields [12]. As shown in [13], the existence of this zero mode persists when we introduce arbitrary (CPT conserving) masses for the fermions, induced by Yukawa couplings.

At temperatures below the electroweak phase transition, we can introduce an effective time-dependent chemical potential $\mu(t)$ with respect to $B + L$. Unsuppressed violation of $B + L$ by sphalerons at high temperatures implies that the initial value of μ is of order the electroweak scale. As time goes on, sphaleron transitions occur in both directions (of increasing or decreasing $B + L$), however there is a bias in favor of transitions that reduce $B + L$. This can be seen by computing the free energy as a function of net fermion number. At high temperatures, for a single species of fermion, the leading behavior is given by

$$F = \Omega - \frac{T^4 (I_0(m) - I_0(\bar{m}))^2}{2(I_1(m) + I_1(\bar{m}))} + \frac{(\langle N - \bar{N} \rangle)^2}{2(I_1(m) + I_1(\bar{m})) T^2} \,, \tag{4.2}$$

where F and Ω are respectively the free energy and the thermodynamic potential per unit volume, and $I_1(m)$ another dimensionless integral related to $I_0(m)$. Note that we have considered in eq. (4.2) the most general case with CPT violating fermion masses. In the usual CPT conserving case the second term vanishes.

It is clear from eq. (4.2) that the free energy is minimized for $B + L = 0$. This produces a bias in the sphaleron transition rate, which reduces the effective chemical potential and $B + L$ towards zero. Letting N_{B+L} denote the $B + L$ number density per unit volume, we can write [14]:

$$\frac{dN_{B+L}}{dt} \sim -\frac{\Gamma N_{B+L}}{T^3} \,, \tag{4.3}$$

where Γ is the sphaleron transition rate per unit volume in the absence of the bias, and we have suppressed numerical factors. Since the sphaleron transition rate in a unit volume is of order $T \sim M_W$, the dilution of the initial $B + L$ is quite rapid.

Now let us consider the effects of CPT violating neutrino masses (or other fermion masses) on the picture just described. First of all, we see immediately from eq. (4.2) that the Dolgov-Zeldovich mechanism will not generate a B asymmetry if sphalerons are the source of B violation. This is because the free energy is minimized for $B + L = 0$, even in the case that CPT is violated. Thus the sphalerons leave a remnant nonzero chemical potential, whose result is precisely to cancel the kinematic effect eq. (4.1) produced by CPT violation.

However, CPT violating fermion masses also have a direct effect on the physical mechanism of $B+L$ violation via level crossing. Qualitatively, CPT violation shifts the spectrum such that an unoccupied positive frequency antifermion state no longer exactly matches a filled negative frequency fermion state. This will induce "confusion" in the level crossing mechanism, such that some fraction of sphaleron transitions have no effect on $B + L$, or produce a change with the opposite sign from that expected. Put more formally, by breaking CPT we have violations of the index theorem that relates the Chern-Simons winding number of the sphaleron configuration to a change in $B + L$.

To estimate this effect, consider our maximally CPT violating model and let m denote both the largest CPT violating neutrino mass difference and the largest neutrino mass. Compared to $m \simeq 1\,\mathrm{eV}$, sphalerons are tiny objects, with a size on the order of $1/M_W$. However, as shown explicitly in [13], the normalizable zero energy mode for massive fermions in the presence of the sphaleron has a characteristic size of order $1/m$, with an inner core whose size is order $1/M_W$. Furthermore from the explicit solution one finds that the total momentum contained in the fermion zero mode solution outside its inner core is of order m.

We thus expect that the fraction of sphaleron transitions which are "confused" by CPT violation is roughly of order m/T. In this case, sphaleron dilution of $B + L$ should become a random walk when the free energy difference between the $B + L$ increasing and decreasing sphaleron transition rates becomes of order m in a unit volume. This implies a residual $B + L$ asymmetry of order m/M_W, roughly the observed magnitude if $m \simeq 1\,\mathrm{eV}$. We expect also that their is some preference in our model to produce a positive residual L, which implies a positive residual B since $B - L = 0$.

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 (as noted already in ref. [7]). Although their original intention was to run primarily in neutrino mode, the other possibility is under consideration [15]. In addition, within this

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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 [16], 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. A CPT violating LMA scenario could then be confirmed in the Borexino experiment [17], by seeing neither a seasonal variation nor a day/night asymmetry. These signatures, as well as the MiniBooNE one, are 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. Predictions in this case are not independent of the realization of CPT violation (i.e. maximal or not).

This scenario, having a Dirac electron antineutrino mass of $\mathcal{O}(1)\,\mathrm{eV}$, 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 [18].

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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