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CPT violating neutrinos in the light of KamLAND

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Abstract

The KamLAND collaboration has observed a medium baseline oscillation signal for reactor antineutrinos. We show that a hierarchical CPT violating neutrino spectrum can simultaneously accommodate the oscillation data from LSND, atmospheric, solar and KamLAND, as well as the nonobservation of antineutrino disappearance in short baseline reactor experiments. In our scenario the KamLAND experiment is not observing an LMA solar oscillation signal. Instead the KamLAND oscillation signal is due to an independent mass splitting in the antineutrino spectrum. A larger antineutrino mass splitting accounts for the LSND signal and also contributes to atmospheric oscillations.

1 Introduction

CPT violating neutrino masses allow the possibility [1] - [4] of reconciling the LSND [5], atmospheric [6], and solar oscillation [7, 8] data without resorting to sterile neutrinos. As argued in [2], there are good reasons to imagine that CPT violating dynamics couples directly to the neutrino sector, but not to other Standard Model degrees of freedom. An explicit CPT violating model of this type was presented in [4].

KamLAND [9], a medium baseline reactor antineutrino disappearance experiment, is sensitive to antineutrino mass-squared splittings in the 10^{-4} eV^2 range characteristic of the large mixing angle (LMA) solar neutrino scenario. The KamLAND collaboration has recently reported [10] an electron antineutrino survival probability which is significantly less than one:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 0.611 \pm 0.085 \pm 0.041 \ . \qquad (1.1)$$

If the neutrino mass spectrum conserves CPT, then this result is consistent with the LMA interpretation of solar neutrino oscillations. If the neutrino mass spectrum violates CPT, however, the KamLAND result provides no information about solar oscillations, but rather constrains the splittings in the antineutrino spectrum.

In this paper we show that a hierarchical CPT violating neutrino spectrum can simultaneously accommodate the oscillation data from LSND, atmospheric, solar and KamLAND, as well as the nonobservation of antineutrino disappearance in short baseline reactor experiments. In our scenario the KamLAND experiment is not observing an LMA solar oscillation signal. Instead the KamLAND oscillation signal is due to an independent mass splitting in the antineutrino spectrum. A larger antineutrino mass splitting accounts for the LSND signal and also contributes to atmospheric oscillations.

2 The spectrum

To analyze all the possible CPT violating spectra is not an easy job. With four mass differences and six mixing angles (not taking into account the two CP violating phases which participate in oscillations) a complete scan of the whole parameter space is impractical. However, thanks to the available experimental data, it is possible to reduce the allowed regions to two sets of well-differentiated spectra with (quasi) orthogonal experimental signatures.

The easiest way to make contact with the experimental results is in terms of the neutrino survival and transition probabilities, which are given by

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j=1}^{3} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2\left[\frac{\Delta m_{ij}^2 L}{4E}\right] \tag{2.1}$$

for neutrinos and

$$P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j=1}^{3} \overline{U}_{\alpha i} \overline{U}_{\beta i} \overline{U}_{\alpha j} \overline{U}_{\beta j} \sin^2\left[\frac{\Delta \overline{m}_{ij}^2 L}{4E}\right] \tag{2.2}$$

for antineutrinos. Here the matrix $U = \{U_{\alpha i}\}$ ($\overline{U} = \left\{\overline{U}_{\alpha i}\right\}$) describes the weak interaction neutrino (antineutrino) states, ν_α, in terms of the neutrino (antineutrino) mass eigenstates, ν_i. That is,

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \qquad \text{and} \qquad \overline{\nu}_\alpha = \sum_i \overline{U}_{\alpha i} \overline{\nu}_i \tag{2.3}$$

where we have ignored the possible CP violation phases in both matrices and took them to be real. The matrices can be parametrized as follows:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix} \tag{2.4}$$

and similarly for $\overline{U}$. In Eq. (2.1) L denotes the neutrino flight path, *i.e.* the distance between the neutrino source and the detector, and E is the energy of the neutrino in the laboratory system.

Regarding the mass spectrum of the three neutrinos we assume that it is hierarchical and thus characterized by two different squared masses

$$\Delta m_{12}^2 = m_2^2 - m_1^2 \quad \text{and } \Delta m_{13}^2 = m_3^2 - m_1^2$$

whose numerical values are rather different, *i.e.* $\Delta m_{13}^2 \gg \Delta m_{12}^2$ and similarly for the antineutrinos. Having said that, it becomes apparent that the larger mass-squared difference in the neutrino sector will be related to the atmospheric neutrino signal observed by SuperKamiokande, while the smaller one will drive the solar neutrino oscillations. In the antineutrino sector, the largest mass difference will provide an explanation to the signal observed in LSND, while the smaller one is the one which might have been (mis)identified by KamLAND as a confirmation of LMA.

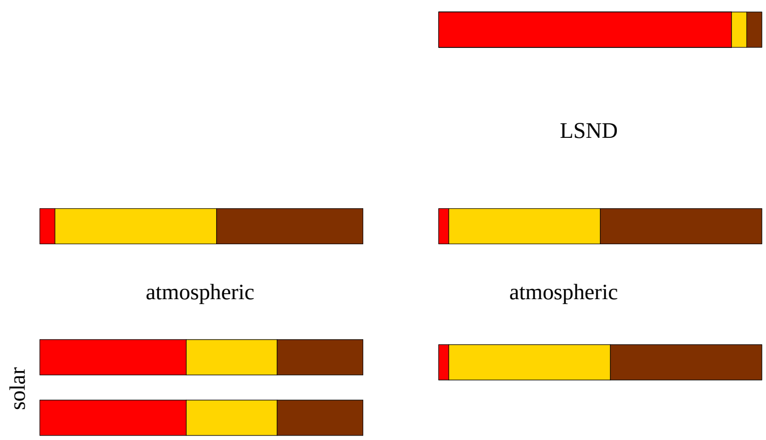

Figure 1: *Possible neutrino mass spectrum with almost all the electron content in the heavy state. Although the figure shows an example of large mixing, our approach is agnostic about the mixing matrix. The flavor content is distributed as follows: electron flavor (red), muon flavor (brown) and tau flavor (yellow)*

The key ingredient to sort out the antineutrino spectra are reactor experiments. Their results indicate [11, 12] that electron antineutrinos produced in reactors remain electron antineutrinos on short baselines. As the distance traveled by our antineutrinos is small we can forget about the smallest mass difference and average the other two, thus the survival probability can be expressed as

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - 2\overline{U}_{e3}^2(1 - \overline{U}_{e3}^2) \ . \tag{2.5}$$

It is clear that there are two possible ways to achieve a survival probability close to one, *i.e.* $\overline{U}_{e3}$ can be almost one or almost zero. Physically this means that we can choose between having almost all the antielectron flavor in the heavy state (or in the furthest away state) or just leave in this state almost no antielectron flavor. The first possibility (which is depicted in Fig. 1) is the one we explored in our previous works. This spectrum predicts for KamLAND a survival probability consistent with one. Since this is strongly disfavored by the KamLAND result (1.1), we instead pursue the second possibility, which is represented by the spectrum shown in Figure 2.

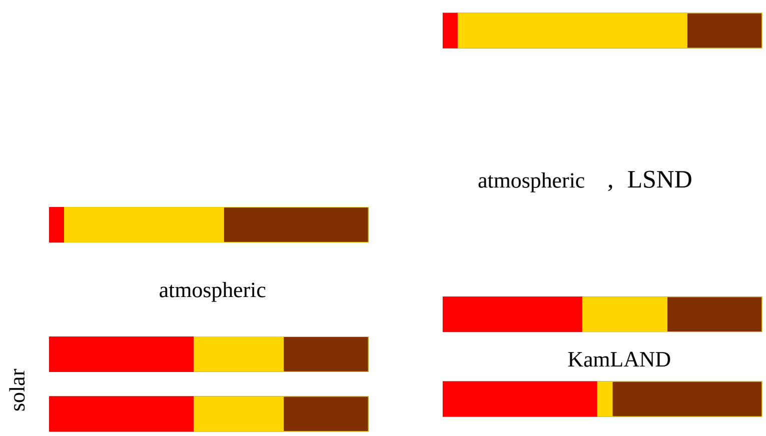

Figure 2: *Possible neutrino mass spectrum with almost no electron content in the heavy state. Although the figure shows an explict mixing pattern, there is a whole family of mixing matrices that can do an equally good job. The flavor content is distributed as follows: electron flavor (red), muon flavor (brown) and tau flavor (yellow)*

This second family of spectra is characterized by a strong violation of CPT in the mass differences but a much slighter effect in the mixing matrix. This is seen in Fig. 2 where the flavor distribution in the neutrino and antineutrino spectra is rather similar. The most distinctive feature of this family of solutions is its θ_{23}, which lives far away from maximal mixing, or in other words which has a large component of antitau neutrino in the heavy state. The small antimuon neutrino component in the heavy state is not bounded by the non observation of muon neutrino disappearance over short baselines in the CDHS experiment[13], as the antineutrino component in this experiment was minimal.

KamLAND could have observed an oscillation signal driven by the smaller antineutrino mass splitting and misinterpreted it as LMA oscillations. To explicitly see how this might have happened, we will choose two sample points in our parameter space and calculate the transition probabilities for it. Let us emphasize that we have not performed a chi-squared fit and therefore the points we are selecting (by eye and not by chi) are not optimized to give the best fit to the existing data. Instead, they must be regarded as two among the many equally good sons in this family of solutions.

The point we have chosen has $\overline{\theta}_{13} = .08$, $\overline{\theta}_{23} = .5$, $\overline{\theta}_{12} = .6$, $\Delta\overline{m}^2_{12} = 5 \cdot 10^{-4}$ eV^2 and $\Delta\overline{m}^2_{13} = \mathcal{O}(1)$ eV^2. Since we are dealing with an antineutrino signal, we do not need to identify either the flavor distribution or the mass eigenstates of the neutrino sector. We will do it later, when showing the zenith angle dependence this model predicts for SuperKamiokande atmospheric neutrinos.

The survival probability measured by KamLAND is given by

$$P_{\text{KamLAND}} = 1 - 4\overline{U}^2_{e3}(1-\overline{U}^2_{e3})\sin^2\left[\frac{\Delta\overline{m}^2_{13}L}{4E}\right] - 4\overline{U}^2_{e1}\overline{U}^2_{e2}\sin^2\left[\frac{\Delta\overline{m}^2_{12}L}{4E}\right] , \quad (2.6)$$

where the second term (proportional to $\overline{U}^2_{e3}$) is negligible. Plugging our numbers in, it is straightforward to see that $P_{\text{KamLAND}} \approx .6$ regardless of whether the mass difference that drives the solar neutrino oscillations belongs to the LMA region.

By the same token, we can calculate the probability associated with the LSND signal. It is given by

$$P_{\text{LSND}} = 4\overline{U}^2_{\mu 3}\overline{U}^2_{e3}\sin^2\left[\frac{\Delta\overline{m}^2_{13}L}{4E}\right] , \quad (2.7)$$

where we have neglected terms proportional to $\Delta\overline{m}^2_{12}$ which are irrelevant for such small distances. As the reader can easily verify, we predict a $P_{\text{LSND}} \simeq .0022$ in excellent agreement with the LSND final analysis:

$$P_{\text{LSND-final}} = 0.00264 \pm .00081 \ . \tag{2.8}$$

The only piece of experimental evidence involving antineutrinos which remains to be checked is the signal found for SuperKamiokande atmospheric neutrinos. As we are introducing an antineutrino mass difference roughly two orders of magnitude larger than the SuperK best fit point (for an analysis with two generations and conserving CPT), there is cause for concern. In fact we pass this test as successfully as we did the others. To see this, we have first to state the parameters in the neutrino sector. Once more they have been chosen almost randomly from the different analyses available in the literature and are given by $\theta_{13} = .08$, $\theta_{23} = .78$, $\theta_{12} = .52$, $\Delta m^2_{12} = 1 \cdot 10^{-4}$ eV^2 and $\Delta m^2_{13} = 2.8 \cdot 10^{-3}$ eV^2. We stress that although we have chosen a point in the LMA region, the particular election of both Δm^2_{12} and θ_{12} does not affect the quality of the agreement with the data.

With these parameters we have calculated the zenith angle dependence of the ratio (observed/expected in the no oscillation case) for muon and electron neutrinos for the sub-GeV and multi-GeV energy ranges (remember that since SuperK is a water Cherenkov detector it does not distinguish neutrinos from antineutrinos and washes out any possible difference between the conjugated channels). The results are shown in Fig. 3 where we have also included the experimental data for the sake of comparison. As we have closely followed the spirit of the calculation in [14, 3], we refer the reader to this article for details and skip the technicalities. We worked in a complete three generation framework and included matter effects.

In Fig. 4 we show the comparison to SuperK for our second example point. For this point we have chosen $\overline{\theta}_{13} = .08$, $\overline{\theta}_{23} = .5$, $\overline{\theta}_{12} = .785$, $\Delta\overline{m}^2_{12} = 7 \cdot 10^{-5}$ eV^2 and $\Delta\overline{m}^2_{13} = \mathcal{O}(1)$ eV^2. Note that this point is consistent with the best-fit point of KamLAND [10].

In order to understand the results it is important to remember that due to production and cross section effects SuperK is dominated by neutrinos, with antineutrinos a minor (but not negligible) contribution. One might wonder though why the analysis done by the SuperK collaboration allowing for CPT violation does not allow (at 99% C.L.) a mass difference in the antineutrino sector so drastically different from the one in the neutrino sector. The answer comes from a variety of sources. The SuperK analysis was not only done in a two generation context but also forcing the two mixing angles to be maximal. This latter fact indeed maximizes the antineutrino contribution and compels the antineutrino mass difference to take the closest possible value to the neutrino one. Leaving the mixing angles and the mass differences free indeed complicates the analysis a lot (to the point where we do not even consider making a complete chi-squared fit to the whole parameter space) but does not risk losing solutions. Instead, we have tried to make an educated guess and search for a point/region that survives all the cuts, so that others (more brave people) will take the following step.

The two vs three generation analysis has also an impact, as is seen by inspecting the transition probability for muon antineutrinos into tau antineutrinos, which is given by,

$$P(\overline{\nu}_\mu \to \overline{\nu}_\tau) = \;=\; 4\overline{U}^2_{\mu 3}\overline{U}^2_{\tau 3}\sin^2\left[\frac{\Delta\overline{m}^2_{23}L}{4E}\right] - 4\overline{U}_{\mu 2}\overline{U}_{\tau 2}\overline{U}_{\mu 1}\overline{U}_{\tau 1}\sin^2\left[\frac{\Delta\overline{m}^2_{12}L}{4E}\right] \quad (2.9)$$

From this formula it becomes apparent that for neutrinos coming from above only the largest mass difference contributes. However, for those neutrinos which have travelled through sizeable portions of the Earth and have covered distances of the order of 10^4 km, the second mass difference also plays a role. This contribution (which does affect the final result, especially for sub-GeV neutrinos) is neglected if only one mass difference is taken into account.

Our analysis agrees with the spirit of the findings in Ref [15] where a two generation approximation that didn't include matter effects was used. Also a simplified analysis based only on the up/down asymmetry in the number of multi-GeV events (in the CPT violating case) is available in the literature [16], which used an older SuperK data set. If one uses (as we do) the result from the full 1490 day of SK-I data, *i.e.* $A_\mu = -.288 \pm .030$ [17] the CPT violating case (which gives for the sample points we have being using $A_\mu = -.27$) is clearly favored over the CPT conserving one ($A_\mu = -.32$). Indeed with the new experimental numbers this is clear also from the discussion in Ref [16]. In all the cases the electron neutrino asymmetry is consistent (within experimental errors) with zero.

3 Discussion

Once we have established that a CPT violating mass spectrum as the one shown in Fig. 2 can account for all the available experimental evidence (including the KamLAND result), it is time to ask how we might confirm CPT violation in future data.

The most straightforward answer is through experiments able to run in both modes (neutrino and antineutrino), by simple comparison of the conjugated channels. The first of them is MiniBooNE, which is meant to close the discussion about LSND one way or the other. MiniBooNE started taking data last summer and is expected to give a definite answer to the CPT question after some years of running in each mode. Needless to say we expect MiniBooNE to confirm LSND only when running in the antineutrino mode.

For our type of spectrum, the observation of atmospheric neutrinos using the MINOS detector [18] is also ideal. Because the MINOS detector discriminates positive and negative charge, this experiment can disentangle the neutrino and antineutrino components of atmospheric oscillations in a straightforward way. As the mass differences in the atmospheric sectors differ by orders of magnitude in our scenario, MINOS will be able to tell them apart easily.

A positive oscillation signal at KamLAND (here assumed to be a misidentification of a CPT violating spectrum as LMA) and Borexino [19] finding a day/night asymmetry (evidence of a LOW solution [20]) or a seasonal variation (an indication of VAC [20]) will point towards CPT violation. Indeed a conflict between KamLAND and Borexino results would constitute strong evidence for CPT violation even if LSND is disconfirmed by MiniBooNE. Note that the best-fit point reported by KamLAND has maximal mixing, which is clearly disfavored by SNO data; more data will be required to determine if this is a real inconsistency.

All in all, CPT violation has the potential to explain all the existing evidence about neutrinos with oscillations to active flavors. Such a scenario makes distinctive predictions that will be tested in the present round of neutrino experiments. One should always bear in mind that so far we have no evidence of CPT conservation in the neutrino sector. Indeed as we have shown, all the existing data, including the zenith angle dependence of the atmospheric muon neutrinos (and antineutrinos) seen by SuperKamiokande, are equivalently explained if CPT is broken in a rather drastic way. The true status of CPT in the neutrino sector might be established by the combined results of KamLAND, Borexino and SNO, and certainly by MiniBooNE. In the atmospheric sector MINOS is the ideal experiment for such a test.

Acknowledgments

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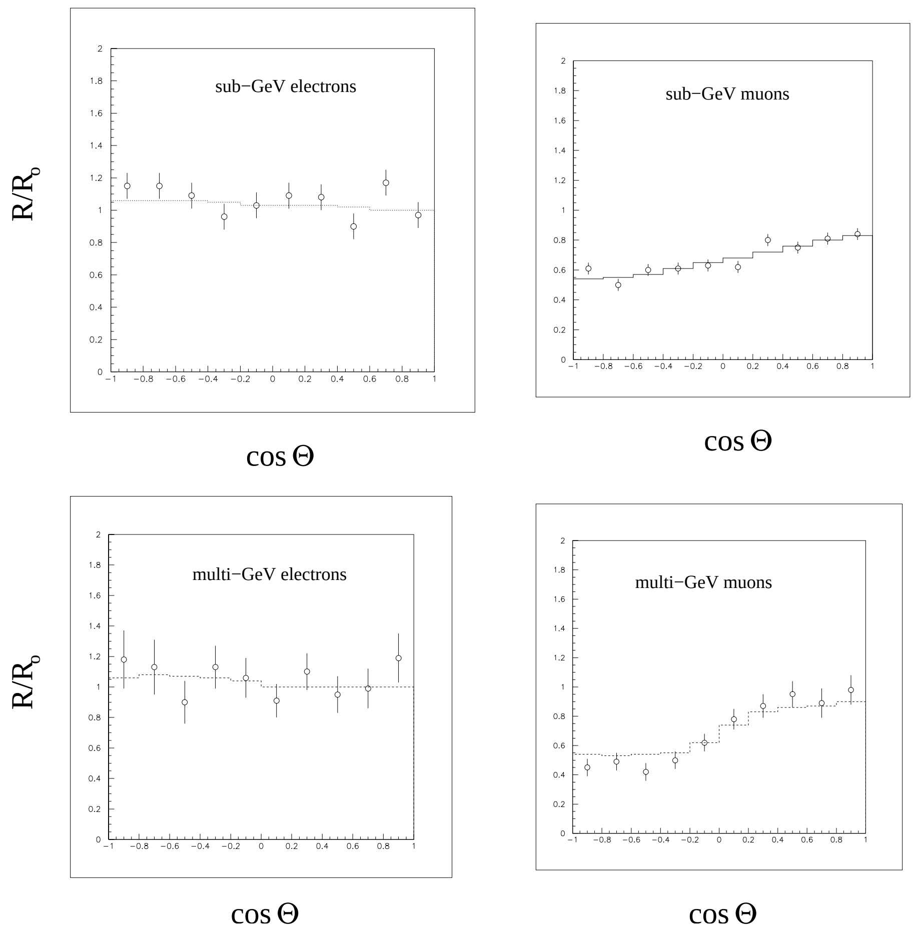

Figure 3: *SK zenith angle distributions normalized to no-oscillations expectations, for our first CPT violating example. Circles with error bars correspond to SK data.*

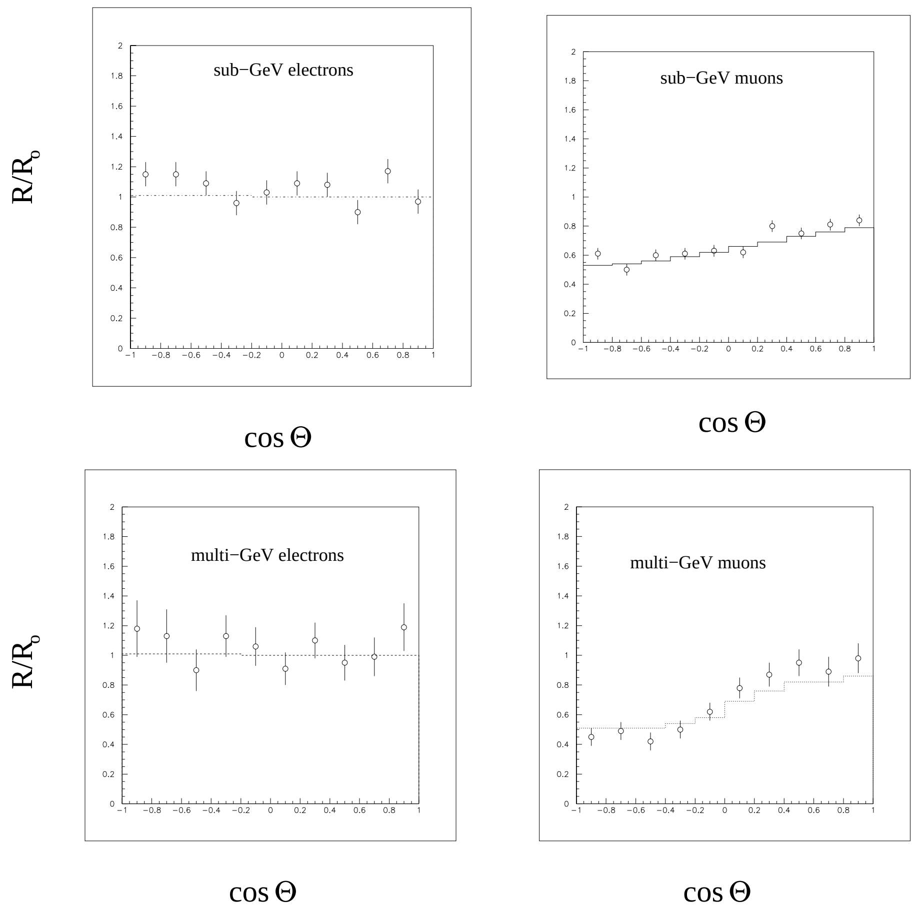

Figure 4: *SK zenith angle distributions normalized to no-oscillations expectations, for our second CPT violating example. Circles with error bars correspond to SK data.*