Probing CPT violation with atmospheric neutrinos

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ABSTRACT

We investigate the recently suggested scheme of independent mass matrices for neutrinos and antineutrinos. Such a CPT violating scheme is able to account for all neutrino data with the three known flavors. For atmospheric neutrinos this means that it is possible to have different mass squared differences driving the oscillation for neutrinos and antineutrinos. We analyze the atmospheric and K2K data within the simplest scheme of two neutrino oscillation, neglecting electron neutrino oscillation. We find that the preferred region is close to the CPT conserving mass spectra. However the spectra with the antineutrino mass squared difference about or larger than 0.1 eV$^2$ and the neutrino mass squared difference about $2 \times 10^{-3}$ eV$^2$ is not significantly disfavored. In this parameter region the atmospheric data are independent of the antineutrino mass squared difference. Therefore no useful constraint can be put on CPT violation effects contributing to different masses for the neutrinos and antineutrinos.

Keywords: Neutrino physics, atmospheric neutrinos, CPT violation.

1 Introduction

Many elementary particles, like the electron and the kaons, provide tight bounds on possible CPT violating effects contributing to different masses for the particle and its antiparticle. For instance for the electron and the positron we have

$$\frac{|m_{e^+} - m_{e^-}|}{m_{\text{average}}} < 8 \times 10^{-9}, \quad \text{CL} = 90\%.$$  \hspace{1cm} (1)

As is well known, CPT conservation implies the equality of the neutrino and antineutrino survival probabilities in vacuum [4], though matter effects can produce fake CPT violating effects [5]. The atmospheric neutrino data involve both the particle and the antiparticle channels and are therefore suitable for a study of possible CPT violation in the neutrino sector. The idea to use neutrino oscillation to search for CPT violation was first proposed in Ref.[4]. Naturally as the atmospheric neutrino experiments are probing mass squared differences and not the absolute neutrino mass, these will be the quantities which might be restricted by the data. The interest in CPT violation arises due to a recently suggested scheme which is capable of solving all neutrino anomalies without the use of a light sterile neutrino [5, 6].

At present three neutrino anomalies (atmospheric [7], solar [8] and LSND [9]) exist, all requiring different $\Delta m^2$’s when interpreted in terms of neutrino oscillation. Therefore a CPT

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conserving three neutrino framework cannot account for all anomalies. This has also been explicitly shown in theoretical fits of the atmospheric data \([10, 11]\). Consequently one has to go beyond standard explanations to solve all anomalies.

A possible solution could be the existence of a light sterile neutrino. Several studies of such four neutrino models have been performed and the current situation has been presented in Ref.\([12]\). The four neutrino models give an acceptable fit when fitting all available data. However, each of the different solutions faces problems within a particular subset of the data. The ’3+1’ mass spectra are in disagreement with the short-baseline experiments and the ’2+2’ mass spectra conflict with either the atmospheric or the solar neutrino data. Therefore the four neutrino models, though not completely ruled out at present, seem highly disfavored.

In the absence of a sterile neutrino, Yanagida and Murayama have recently suggested another possibility to solve all of the known neutrino anomalies \([5]\). The Yanagida-Murayama scheme preserves Lorentz invariance\(^2\) but involve CPT violation by invoking independent masses for neutrinos and antineutrinos. Hence there is a total of four independent \(\Delta m^2\)’s. Schematically we can represent the masses for the neutrino and antineutrino as in Fig.2. The solar neutrino problem only concerns the disappearance of \(\nu_e\) and the LSND experiment sees \(\nu_e\) appearance in a \(\nu_\mu\) beam. These experiments can be separately explained by \(\Delta m^2_\odot\) and \(\Delta m^2_{\text{LSND}}\) in the Yanagida-Murayama scheme. The atmospheric neutrinos data involve both \(\nu_\mu\) and \(\bar{\nu}_\mu\) and allowing for CPT violation the two \(\Delta m^2\)’s are no longer constrained to be identical as also considered in Refs.\([14, 6]\). It is therefore clear that all the data can be explained within this model.

To invoke CPT violation is indeed a very drastic solution. Therefore it is important to discuss physical models for generating CPT violation in the Yanagida-Murayama scheme. In Ref.\([1]\) a definite model of CPT violation is introduced that can account for all available neutrino data. It was argued that CPT violation in the neutrino sector can be motivated from string theory via the extra dimensions. The right-handed neutrinos, like the graviton, are free to propagate in the bulk, whereas the Standard Model fields are constrained within a four dimensional brane. This gives rise to non-locality for the neutrinos and thereby generating CPT violation. This CPT violating scheme is also able to account for baryogenesis in a natural way \([6]\). Furthermore non-commutative geometry can generate CPT violation \([15, 5]\).

In this paper we will study the atmospheric neutrino anomaly within a two family neutrino scheme with CPT violation. The electron neutrinos are assumed not to oscillate on the atmospheric scale. We include the data from the K2K long baseline experiment, that further constrain the neutrino parameters. The atmospheric neutrino problem is by now well established and can be accounted for primarily by a two neutrino \(\nu_\mu \rightarrow \nu_\tau\) oscillation \([7]\). However,

\(^2\)It has been argued that the scheme also violate Lorentz invariance \([13]\)
sub-dominant oscillations are still possible and maybe even welcome \cite{16, 11}. Having different mass matrices for neutrinos and antineutrinos naturally gives different mixing matrices; $U_\nu$ for the neutrino sector and $U_\bar{\nu}$ for the antineutrino sector. We will investigate whether the mixing parameters can be constrained by the atmospheric and K2K data. A most relevant parameter is the difference in mass squared difference for neutrinos and antineutrinos. Let us define the parameter $\epsilon$ to describe the amount of CPT violation

$$\epsilon = |\Delta m^2_{\nu,\text{atm}} - \Delta m^2_{\bar{\nu},\text{atm}}|.$$  

(2)

Using the latest data, we will show that $\epsilon$ is only weakly constrained.

Let us finally mention that the LSND result, which has not yet been confirmed, will be scrutinized by the Mini-BooNE experiment \cite{17}. However, as has been noted before, unless this experiment is done also with antineutrinos the Yanagida-Murayama scheme cannot be ruled out.

## 2 Analysis of the atmospheric data

A number of experiments have measured the atmospheric neutrino fluxes. Here we will only consider the contained events of the Super-Kamiokande (SK) experiment \cite{18}. The justification for leaving out other data sets is the superior statistics of the SK data. Furthermore, the high energy upward through-going muon events \cite{19} are less affected by antineutrinos. For the average energy of 100 GeV of these events the $\nu_\mu/\bar{\nu}_\mu$ flux ratio is about 1.5, thus decreasing the influence of the antineutrinos. Also the statistics is lower and we do not expect large effects from the inclusion of this sample.

We use the following simple two-family survival probability relations for neutrinos and antineutrinos

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta_\nu) \sin^2 \left( \frac{L \Delta m^2_{\nu}}{4E} \right),$$  

(3)

$$P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} = 1 - \sin^2(2\theta_\bar{\nu}) \sin^2 \left( \frac{L \Delta m^2_{\bar{\nu}}}{4E} \right).$$  

(4)

We assume that the oscillation is into $\tau$-neutrinos, whereby the electron survival probability is taken to be one for both neutrinos and antineutrinos. As we only consider $\nu_\mu$ to $\nu_\tau$ oscillation there are no matter effects. The pathlength of the neutrino, $L$, is calculated using an average production point in the atmosphere of 15km. $E$ is the neutrino energy.

The data are divided into sub-GeV and multi-GeV energy ranges and can be represented as the ratio, $R^{\text{exp}}$, between the measured fluxes and the theoretical Monte Carlo prediction in the case of no oscillation. We define $\chi^2$ as

$$\chi^2 = \sum_{M,S} \sum_{\alpha=e,\mu} \sum_{i=1}^{10} \frac{(R_{\alpha,i}^{\text{exp}} - R_{\alpha,i}^{\text{th}})^2}{\sigma_{\alpha,i}^2} + \chi^2_{\beta},$$  

(5)

where $\sigma_{\alpha,i}$ are the statistical errors and $M, S$ stand for the multi-GeV and sub-GeV data respectively and $i$ denotes the zenith angle bin. For the details of the $\chi^2$ definition we refer to Ref.\cite{11}, except that we here use a smearing of the sub-GeV events with an angle $50^\circ/\sqrt{E_\nu/\text{GeV}}$ \cite{20}. The overall normalization of the neutrino fluxes is allowed to vary freely. Hence we minimize with respect to $\alpha$, where the neutrino flux is given by $\Phi = (1 + \alpha)\Phi^0$. The theoretically predicted neutrino flux $\Phi^0$ is taken from \cite{21, 22}. The $\chi^2_{\beta}$ term takes into account
Figure 2: The 68.3% (90%) CL regions for parameters $\Delta m^2_{\nu}$ and $\Delta m^2_{\bar{\nu}}$ for the contained SK events and the total number of events in K2K (5 d.o.f).

the error in the $\nu_\mu/\nu_e$ flux ratio. The SK Collaboration estimate the error to be 8% in the sub-GeV range and 12% in the multi-GeV range. We renormalize the neutrino fluxes as

$$\tilde{\Phi}^{S,M}_\mu = (1 - \beta_{S,M}/2)\Phi^{S,M}_\mu, \quad \tilde{\Phi}^{S,M}_e = (1 + \beta_{S,M}/2)\Phi^{S,M}_e$$

where the symbols $S, M$ stands for sub-GeV and multi-GeV respectively and minimize the total $\chi^2$ function with respect to $\beta_S$ and $\beta_M$. The $\chi^2_\beta$ function is given by

$$\chi^2_\beta = \left( \frac{\beta_S}{0.08} \right)^2 + \left( \frac{\beta_M}{0.12} \right)^2.$$ (7)

For the best fit point obtained by the SK Collaboration the values used are $\beta_S = 6\%$ and $\beta_M = 12\%$, implying that while scaling the electron ratios down one simultaneously scales the muon ratios up.

We also include the recent data from the K2K long baseline experiment [23]. The beam is almost pure $\nu_\mu$ and we will neglect the small contamination of $\bar{\nu}_\mu$ and $\nu_e$. We use the same method as in Ref.[24] and only fit to total number of observed events. In total we have five parameters ($\Delta m^2_{\nu}, \Delta m^2_{\bar{\nu}}, \theta_\nu, \theta_{\bar{\nu}}, \alpha$) and 41 data points.

The minimum is $\chi^2_{\text{min}} = 33$ at $\alpha = 1\%, \beta_S = 8\%, \beta_M = 10\%$ and

$$\Delta m^2_{\nu} = 2.5 \times 10^{-3} \text{ eV}^2, \quad \Delta m^2_{\bar{\nu}} = 2.0 \times 10^{-3} \text{ eV}^2, \quad \sin^2(2\theta_\nu) = 1.0, \quad \sin^2(2\theta_{\bar{\nu}}) = 1.0$$ (8)

with 36 degrees of freedom. This is very close to the CPT conserving case. In Fig.4 we show the 68.27% and 90% confidence levels as obtained by $\Delta \chi^2 < 5.9, 9.2$, respectively, for five degrees of freedom. At 90% C.L. the mass squared difference for neutrinos is constrained within $4.5 \times 10^{-4} \text{ eV}^2 - 5 \times 10^{-3} \text{ eV}^2$, while the antineutrino mass squared difference is only bounded from below ($> 2 \times 10^{-4} \text{ eV}^2$). At 90% C.L. the mixing angles are bounded, $\sin^2(2\theta_\nu) > 0.8$ and $\sin^2(2\theta_{\bar{\nu}}) > 0.5$, but maximal mixing is preferred for both angles.
The correlation between the lepton and the neutrino angle in the sub-GeV range is very weak and the data is smeared compared to the multi-GeV sample [25]. The exact calculation method can therefore change the results slightly as the effect of a large $\Delta m_2^2$ is similar to a smearing. For smaller effective smearing the best fit point will move toward larger values of $\Delta m_2^2$. The same considerations apply to the mixing angles which also effectively flatten the zenith angle curve.

One should note that a point with values of $\Delta m_2^2 \simeq 0.1$ eV$^2$ and $\Delta m_2^2 \simeq 2 \times 10^{-3}$ is not significantly disfavored. The SK contained data become independent of $\Delta m_2^2$ in this region as the oscillation probabilities are averaged to 1/2 for all pathlengths. K2K is obviously independent of $\Delta m_2^2$ as they measure neutrinos. The predicted ratios of this mass spectra are shown in Fig. 3 along with the data points. The predicted ratio of around 0.85 for the downward going multi-GeV muon neutrinos can be easily understood. In this energy range the flux of neutrinos is roughly the same as the flux of antineutrinos. But the antineutrino cross section is less than half that of neutrinos. The $\sin^2(\frac{L\Delta m^2}{4E})$ is averaged to one half for antineutrinos and to one for neutrinos and the ratio is estimated to

$$R_{\mu,\downarrow} \simeq \frac{\Phi_{\mu_\mu} P_{\mu_\mu \rightarrow \nu_\mu} \sigma_{\nu_\mu} + \Phi_{\mu_\mu} P_{\mu_\mu \rightarrow \nu_\mu} \sigma_{\nu_\mu}}{\Phi_{\nu_\mu} \sigma_{\nu_\mu} + \Phi_{\mu_\mu} \sigma_{\nu_\mu}} \simeq 0.85,$$

where $\sigma$ is the cross section. The reason that this mass spectra is not strongly disfavored is because it agrees very well with the well known double ratio. The measured value is

$$R = \frac{(\mu/e)_{\text{DATA}}}{(\mu/e)_{\text{MC}}} = 0.675^{+0.034}_{-0.032} \pm 0.080$$

in the multi-GeV range [18]. The prediction double ratio for $\Delta m_2^2 \simeq 2 \times 10^{-3}$ eV$^2$ and $\Delta m_2^2 \simeq 0.1$ eV$^2$ are $R \simeq 0.68$, whereas for both $\Delta m^2$'s around $3 \times 10^{-3}$ eV$^2$ we get $R \simeq 0.75$. 

Figure 3: Predicted ratios as a function of the zenith angle for mixing parameters; $\Delta m_2^2 = 2 \times 10^{-2}$ eV$^2$, $\Delta m_2^2 = 0.1$ eV$^2$ and maximal mixing, and the data with statistical errors. The upper curves are the $\nu_e$ ratios and the lower curves are the $\nu_\mu$ ratios. The triangles are the $\nu_e$ experimental ratios and the circles are the $\nu_\mu$ experimental ratios. Note that the experimental ratios are plotted using $\tilde{\Phi}$ and not $\Phi^0$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Predicted ratios as a function of the zenith angle for mixing parameters; $\Delta m_2^2 = 2 \times 10^{-2}$ eV$^2$, $\Delta m_2^2 = 0.1$ eV$^2$ and maximal mixing, and the data with statistical errors. The upper curves are the $\nu_e$ ratios and the lower curves are the $\nu_\mu$ ratios. The triangles are the $\nu_e$ experimental ratios and the circles are the $\nu_\mu$ experimental ratios. Note that the experimental ratios are plotted using $\tilde{\Phi}$ and not $\Phi^0$.}
\end{figure}
Therefore we find the error of the overall normalization is large and a rise can not be excluded. Predictions \[31\], which roughly amount to putting the normalization back to the old value.

When the SK Collaboration obtains $\alpha$ these ratios. Though the LSND angle is constrained to be small by the BUGEY results. Also a relatively large LSND angle \[11\] as well as the solar mass squared difference \[27\] can influence it for a flux normalization that diminishes the excess of in particular sub-GeV events also agrees well with the muon ratios. In fact in the case that the overall normalization is varied freely, but the $\mu/e$ ratio is kept fixed, the best fit point is for $\Delta m^2_{\nu} \gg \Delta m^2_{\odot}$. Although such a mass spectra does not fit the up-down asymmetries that well as seen from Fig.3. It must be remembered that the measured values quoted in Eq.\[10\] is dependent on the theoretical predictions for the $\nu_\mu/\nu_e$ flux ratio. The double ratio basically describes the average gap between the $\nu_e$ and the $\nu_\mu$ ratios and this gap is somewhat too large to be fitted very well by a CPT conserving two family $\nu_\mu \rightarrow \nu_\tau$ oscillation. However if the theoretically predicted $\nu_\mu/\nu_e$ flux ratio is decreased by 6-12% this provides a very good fit to the data. Furthermore the low value of the double ratio could be due to an excess of $\nu_e$ events which is not accounted for by the two family scheme. The $\chi^2$ value for the point in Fig.3 is 39 and therefore barely outside the 1$\sigma$ region. When using 2 d.o.f. as in Ref.\[26\] this would be a 2$\sigma$ exclusion. We remark that there is a local maximum of the $\chi^2$ function for values of $\Delta m^2_{\nu}$ between $10^{-2} - 10^{-1}$ eV$^2$. The main differences between our results and those in Ref.\[20\] are due to the fact that we use the theoretical predicted fluxes, whereas the normalization in each type of events are varied freely in Ref.\[26\].

For almost all mixing parameters a rise of the theoretical fluxes are needed. New calculations suggest instead a lower flux, by about 10% \[30\], mainly due to the primary flux being lower than obtained in earlier measurements. The new normalization results in a large excess of $\nu_e$ events which seems to be difficult to obtain theoretically. In the conventional CPT conserving case the SK Collaboration obtains $\alpha = 20\%$ for the best fit point using the new flux predictions \[31\], which roughly amount to putting the normalization back to the old value. Therefore we find the error of the overall normalization is large and a rise can not be excluded.

In the CPT violating scheme the electron ratios can be considerably away from one. A relatively large LSND angle \[11\] as well as the solar mass squared difference \[27\] can influence these ratios. Though the LSND angle is constrained to be small by the BUGEY results. Also the two angles $\theta^\nu_{e\mu}$ and $\theta^\nu_{e\tau}$, describing the oscillation of $\nu_e$ driven by the atmospheric mass squared difference, can have effects. In particular $\theta^\nu_{e\mu}$ is not constrained by the CHOOZ \[28\] and Palo Verde \[23\] results as these experiments are measuring anti neutrinos. Moreover $\theta^\nu_{e\mu}$ can be large if $\Delta m^2_{\nu}$ is below the CHOOZ sensitivity of $10^{-3}$ eV$^2$, which is not ruled out by the present data (see Fig.2). The influence of some of these extra mixing parameters has been studied in Ref.\[32\], where however the systematic errors in the SK data have been ignored.

As we have shown the limits on CPT violation in the neutrino sector are rather weak at present. There are nevertheless good prospects for a much stronger bound in the near future. The results from the KamLAND experiment \[33\] could likely disprove the Yanagida-Murayama scheme. The experiment will test the currently favored large mixing angle MSW (LMA) solution to the solar neutrino problem, by detecting anti electron neutrinos from nearby nuclear reactors. For the most favored region of the LMA solution ($\Delta m^2_{\nu} < 2 \times 10^{-4}$ eV$^2$) the detected energy spectrum at KamLAND will quite precisely determine the value of the mass squared difference and this signal would rule out the Yanagida-Murayama scheme. However for $\Delta m^2 > 2 \times 10^{-4}$ eV$^2$ the oscillations are averaged out and KamLAND can only put a lower bound on the anti neutrino mass squared difference \[34\]. In this case the situation becomes more problematic as there are two different possible explanations. A large value of $\Delta m^2_{\nu}$ is not ruled out, though disfavored by the present data. The signal could also be explained within the Yanagida-Murayama scheme by having a small $\Delta m^2_{\nu,atm}$ along with a large $\theta^\nu_{e\mu}$. Borexino detecting solar neutrinos will not be able to pin down the true solution.
Hence, if an averaged oscillation with a large angle is observed, one would most likely have to wait for the results of the MiniBooNE experiment. In the case that KamLAND does confirm the LMA solution to the solar neutrino problem, much better limits on CPT violation could be obtained as discussed in Ref.\cite{[35]}. If Kamland does not observe a suppression of the anti-neutrino flux there are different possibilities to test CPT violation as discussed in Refs.\cite{[26, 32]}. Indirect limits can also be obtained by studying how radiative corrections communicate the large amount of CPT violation in the neutrino sector to the charged lepton sector \cite{[36]}

In conclusion we have analyzed the Super-Kamiokande contained events and the K2K data in a CPT violating two neutrino $\nu_\mu, \nu_\tau$ framework. The best fit area is close to the CPT conserving case. However at present the CPT violation parameter $\epsilon$, defined in Eq.\cite{[4]}, cannot be usefully constrained.

Acknowledgment
The author expresses her thanks to Gabriela Barenboim and Amol Dighe for collaboration when developing the program used in this analysis. Furthermore the author is grateful to Cecilia Jarlskog for discussions and encouragements.

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