Fermilab FERMILAB-Pub-02/060-T June 2002

FERMILAB-Pub-02/060-T
hep-ph/0204077

Can a CPT Violating Ether Solve ALL Electron (Anti)Neutrino Puzzles?

André de Gouvêa

Theoretical Physics Division, Fermilab
P.O. Box 500, Batavia, IL 60510, USA

Abstract

Assuming that CPT is violated in the neutrino sector seems to be a viable alternative to sterile neutrinos when it comes to reconciling the LSND anomaly with the remainder of the neutrino data. There are different (distinguishable) ways of incorporating CPT violation into the standard model, including postulating $m \neq \bar{m}$. Here, I investigate the possibility of introducing CPT violation via Lorentz-invariance violating effective operators ("Ether" potentials) which modify neutrino oscillation patterns like ordinary matter effects. I argue that, within a simplified two-flavor–like oscillation analysis, one cannot solve the solar neutrino puzzle and LSND anomaly while still respecting constraints imposed by other neutrino experiments, and comment on whether significant improvements should be expected from a three-flavor analysis. If one turns the picture upside down, some of the most severe constrains on such CPT violating terms can already be obtained from the current neutrino data, while much more severe constraints can arise from future neutrino oscillation experiments.

1 Introduction

Assuming that neutrinos have a small mass and mix is by far the simplest solution to the two well established Solar [1] and Atmospheric [2] Neutrino Puzzles and the more controversial LSND Anomaly [3]. It is, however, well known that in order to solve all three problems at once, one is required to add new light degrees of freedom to the Standard Model (SM), usually sterile neutrinos. The reason for this is the fact that the Solar Neutrino Puzzle (SNP) requires a neutrino mass-squared difference $\Delta m^2 \lesssim 10^{-4}$ eV^2, the Atmospheric Neutrino Puzzle (ANP) requires 10^{-3} eV$^2 \lesssim \Delta m^2 \lesssim 10^{-2}$ eV^2, and the LSND Anomaly (LA) requires $\Delta m^2 \gtrsim 10^{-1}$ eV^2. With three neutrino mass eigenstates, one can only obtain two independent mass-squared differences.

It has recently been pointed out that there is another way to address all neutrino puzzles with only three neutrino species: CPT violation [4]. It is easy to note that, while the SNP involves neutrinos, the LA points to evidence for oscillation only in antineutrinos,* meaning that if the Δm^2's were different in the neutrino and antineutrino sectors, the three problems could be solved without the addition of light degrees of freedom to the SM. Furthermore, CPT violation in the neutrino sector had already been evoked as a possible solution to inconsistencies in the neutrino data from SN1987A [5].

CPT is the only global space-time symmetry of the SM. Unlike its "broken siblings" (C, P, T, CP, CT, PT), however, CPT invariance is not an accidental/optional symmetry of a quantum field theoretical system. CPT invariance is a consequence of the fact that all microscopic phenomena

*Originally, the LA manifested itself also in the neutrino channel. This effect, however, has disappeared after more data was analyzed [3].

observed to date can be perfectly described by a Lorentz invariant, local Quantum Field Theory [6]. CPT violation implies, necessarily, violation of Lorentz invariance and/or Locality (and, perhaps, a formalism different from Quantum Field Theory...). It has recently been stressed [7] that allowing particle and antiparticles to have different masses seems to imply that *both* Lorentz invariance and Locality are violated.[†]

CPT violating effects can be mimicked by neutrino interactions with a CPT violating medium. Indeed, neutrinos and antineutrinos acquired different *effective* masses while propagating in the presence of matter, such that large matter induced CPT violating effects can be potentially observed in future neutrino experiments. The authors of [8] have mentioned that one may be able to parameterize the CPT violating effects by assuming the existence of a CPT violating *Ether*, which modifies the oscillation probabilities of neutrinos and antineutrinos in distinct ways. Certain advantages come out of such a parameterization: the theory remains local (only Lorentz Invariance is violated), and all well known quantum field theoretical techniques can be safely used to explore other consequences of the postulated CPT violation – CPT violating effects are parametrized by an effective Lagrangian.

I argue, by performing a two-flavor analysis, that the neutrino puzzles and the LA probably cannot be solved in a satisfactory way by assuming the existence of a "CPT violating Ether."[‡] Furthermore, it turns out that the current neutrino data already may set very strong limits on particular CPT violating operators [9], while potentially stronger limits may be imposed by future neutrino experiments, such as KamLAND [10] and Borexino [11].

In Sec. 2, the CPT violating formalism is introduced and motivated. In Sec. 3, I discuss what are the requirements for solving the SNP and the LA within the formalism introduced in Sec. 2, and show why it does not work properly, at least in a two-flavor analysis. I comment briefly on whether one should expect a three-flavor analysis to be more successful. Sec. 4 contains a summary of the results and some discussions, including current and future constraints on CPT violation.

2 On the Formalism

For simplicity, I'll assume that the neutrinos are Majorana particles, and describe it using two-component Weyl spinors. This being the case, after electroweak symmetry breaking,

$$\mathcal{L} = i\bar{\chi}\bar{\sigma}^{\mu}\partial_{\mu}\chi - \frac{m}{2}\chi\chi - \frac{m}{2}\bar{\chi}\bar{\chi} + \mathcal{L}_{\rm int}, \tag{2.1}$$

where χ is a two-component (left-handed) Weyl field, $\bar{\chi} \equiv (\chi)^{\dagger}$, $\bar{\sigma}^{\mu} = (1, \vec{\sigma})$, and $\mathcal{L}_{\rm int}$ contains all the interaction terms.[§]

In the spirit of [12, 9], we assume that possible CPT violating effects are a consequence of unknown ultraviolet physics, and that they are small (as required by experiments). This allows one to write CPT violating effective operators, which are proportional to some order parameter (v.e.v) and suppressed by powers of the new physics scale. Therefore,

$$\mathcal{L}_{\rm CPTV} = -\sum \lambda\langle T\rangle \frac{\mathcal{O}_n}{\Lambda^{(n-3)}} = -A_{\mu}\bar{\chi}\bar{\sigma}^{\mu}\chi - \sum_{n=4}^{\infty} \lambda\langle T\rangle \frac{\mathcal{O}_n}{\Lambda^{(n-3)}}, \tag{2.2}$$

where Λ is the new physics scale, λ are dimensionless coupling constants, $\langle T\rangle$ is the CPT violating order parameter and $\mathcal{O}_n$ are operators composed of the SM fields with mass dimension n, such that $T\mathcal{O}_n$ is a Lorentz invariant operator of mass dimension $n+1$. The lowest dimensional CPT violating

[†]There is a controversy related to whether Lorentz invariance is violated under these circumstances. I thank Gabriela Barenboim for pointing this out.

[‡] The "Ether" is properly defined in Sec. 2.

[§]It is worthwhile to comment in passing that already at this level it is possible to break CPT by saying that there are two masses $m \neq \bar{m}$.

operator comes at $n = 3$ [12], and is parametrized as $A_\mu \bar{\chi}\bar{\sigma}^\mu \chi$, where A_μ is a *constant* four-vector with mass dimension 1. Note that there are no other $n = 3$ CPT violating terms. Hence forth, we ignore all other terms, which are suppressed by powers of $1/\Lambda$, and work with the Lagrangian

$$\mathcal{L} = i\bar{\chi}\bar{\sigma}^\mu \partial_\mu \chi - \frac{m}{2}\chi\chi - A_\mu \bar{\chi}\bar{\sigma}^\mu \chi - \frac{m}{2}\bar{\chi}\bar{\chi} + \mathcal{L}_{\rm int}. \tag{2.3}$$

A_μ can be interpreted in a variety of ways. For example, it looks like a background, classical "electromagnetic" field. In the case of neutrinos, it proves useful to interpret it as a "matter potential." This is because, in the case of electron neutrinos propagating in the presence of, say, nonrelativistic electrons, one obtains exactly $A_\mu \bar{\chi}\bar{\sigma}^\mu \chi$, with $A_\mu = (\sqrt{2}G_F N_e, 0, 0, 0)$, where N_e is the electron number density.

From Eq. (2.3), one obtains the modified Dirac equations

$$\begin{aligned}(i\partial_\mu - A_\mu)[\bar{\sigma}^\mu]^{\dot{\alpha}\alpha}\chi_\alpha - m\bar{\chi}^{\dot{\alpha}} &= 0,\\ (i\partial_\mu - A_\mu)\bar{\chi}_{\dot{\alpha}}[\bar{\sigma}^\mu]^{\dot{\alpha}\alpha} - m\chi^\alpha &= 0,\end{aligned} \tag{2.4}$$

where $\alpha, \dot{\alpha} = 1, 2$ are spinor indices. From Eqs. (2.4), it is easy to calculate the dispersion relation for both the neutrino (positive energy state) and the antineutrino (negative energy state), namely

$$(\pm p - A)^2 - m^2 = 0, \tag{2.5}$$

where the plus sign applies for the neutrino and the minus sign for the antineutrino. The opposite sign for neutrinos and anti-neutrinos is easy to understand if one looks at A_μ as a background classical vector field – particle and antiparticle have opposite charge. It is convenient to choose $A_\mu = (V, 0, 0, 0)$[¶] such that

$$E = \pm V + \sqrt{|\vec{p}|^2 + m^2}. \tag{2.6}$$

As one can readily note, V can be interpreted as a "Ether-induced potential energy." In the case of ordinary matter effects, V is sometimes related to an "effective mass." We comment on this interpretation in the next section, and argue that it can be rather misleading.

3 Addressing the Solar Puzzle plus the LSND Anomaly

The LA can be interpreted as a measurement of $\bar{\nu}_\mu \to \bar{\nu}_e$-conversion with $P_{\mu e} \sim 0.2\%$. The neutrino energies explored range (roughly) from 30 MeV to 55 MeV, and the neutrino travel distance is $L = 30$ m. An interpretation in terms of two-flavor neutrino oscillations indicates, after including constraints from other experiments, that $0.1~\text{eV}^2 \lesssim \Delta m^2 \lesssim 2~\text{eV}^2$, while $10^{-3} \lesssim \sin^2 2\theta \lesssim 10^{-2}$ [3].

The SNP is best interpreted by $\nu_e \to \nu_{\mu,\tau}$-conversion, with $P_{ee} \lesssim 0.5$. The neutrino energies explored range (roughly) from 0.1 MeV to 10 MeV, and the neutrino travel distance is (of course) one astronomical unit, and there is information regarding the survival probability as a function of neutrino energy. Most importantly, the presence of matter inside the Sun and the Earth affects the oscillation pattern significantly. An interpretation in terms of two-flavor neutrino oscillations indicates, after including constraints from other experiments, that $10^{-9}~\text{eV}^2 \lesssim \Delta m^2 \lesssim 10^{-3}~\text{eV}^2$, while $0.1 \lesssim \tan^2\theta \lesssim 10$[*] [13, 14].

The question one would like to address is whether the presence of the Ether-terms described in the previous section can solve both the LA and the SNP. I will restrict the discussion to two-flavor oscillations. This simplifying assumption will render the discussion more clear, and can easily be extended to the three neutrino case. Note that the two-flavor case does fit trivially into a three flavor framework if one chooses the Ether to act only on the "1–2" system, and that there is no ν_e on the

¶Henceforth, I assume that A_μ is time-like.

*The small mixing angle solution to the SNP is currently excluded at the 95% confidence level.

"3" mass eigenstate. The differential equation that will lead to the oscillations in the presence of an electron number density N_e can be written as (assuming that the neutrino energy is much larger than its mass and dropping terms proportional to the identity matrix)

$$i\frac{\mathrm{d}}{\mathrm{d}L}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = \left[\frac{\Delta m^2}{2E_\nu}\begin{pmatrix}\sin^2\theta & \cos\theta\sin\theta\\ \cos\theta\sin\theta & \cos^2\theta\end{pmatrix} + \begin{pmatrix}V & V_{ex}/2\\ V_{ex}^*/2 & 0\end{pmatrix} + \begin{pmatrix}\sqrt{2}G_F N_e & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}, \quad (3.1)$$

where $V_{\alpha\beta}$, $\alpha,\beta = e, x$ are the Ether terms, ν_x is a linear combination of ν_μ and ν_τ, and $V \equiv V_{ee} - V_{xx}$. The equation for antineutrinos is identical to Eq. (3.1) with $V_{\alpha\beta} \to -V_{\alpha\beta}$ and $N_e \to -N_e$. For *fixed* V, V_{ex} the entire solar neutrino parameter space is spanned by assuming $0 \leq \theta \leq \pi$ after one defines the sign of Δm^2 [15]. However, since we will be trying to determine V, V_{ex} from neutrino data, their sign can be adjusted such that $0 \leq \theta \leq \pi/2$, as customary.†

In the absence of matter effects, the oscillation probability is (these have already been presented in [9, 17])

$$P_{ex} = P_{xe} = \sin^2 2\theta_{\rm eff}\sin^2\left(\frac{\Delta_{\rm eff}}{2}L\right) \quad (3.2)$$

where

$$\Delta_{\rm eff} = \sqrt{(\Delta\sin 2\theta + V_{ex})^2 + (\Delta\cos 2\theta - V)^2}, \quad (3.3)$$

$$\Delta_{\rm eff}\cos 2\theta_{\rm eff} = \Delta\cos 2\theta - V, \quad (3.4)$$

$$\Delta_{\rm eff}\sin 2\theta_{\rm eff} = \Delta\sin 2\theta + V_{ex}, \quad (3.5)$$

and $\Delta \equiv \Delta m^2/2E_\nu$. V_{ex} is assumed real henceforth.

For solar neutrinos, we will concentrate on solutions where the adiabatic condition for propagation inside the Sun holds (this will always be the case here, as will be argued later), such that, for a neutrino produced close to the Sun's core,

$$P_{ee} = \tfrac{1}{2} + \tfrac{1}{2}\cos 2\theta_M\cos 2\theta_{\rm eff}, \quad (3.6)$$

$$\cos 2\theta_M = \frac{\Delta\cos 2\theta - (\sqrt{2}G_F N_e^0 + V)}{\sqrt{(\Delta\sin 2\theta + V_{ex})^2 + (\Delta\cos 2\theta - V - \sqrt{2}G_F N_e^0)^2}}, \quad (3.7)$$

with N_e^0 the electron number density in the Sun's core, which translates into $\sqrt{2}G_F N_e^0 \simeq 6\times 10^{-6}$ eV^2/MeV.

The next step is to search for $V, V_{ex}, \Delta m^2$ and θ such that both the LA and SNP are solved, and such that other experimental results are not contradicted.

First, I address the case $V_{ex} = 0$. The LA requires $P_{\bar{x}\bar{e}} \sim 0.5\%$, assuming that $P_{\bar{\mu}\bar{e}} = 0.5 P_{\bar{x}\bar{e}}$, such that the atmospheric neutrino puzzle is solved by maximal $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (the factor of 0.5 will play no role in the following discussions). Using Eq. (3.2) for antineutrinos,

$$P_{\bar{x}\bar{e}} \sim \left(2.54\frac{\Delta}{1~\rm eV^2/MeV}\sin 2\theta\frac{L}{1~\rm m}\right)^2, \quad (3.8)$$

as long as $\bar{\Delta}_{\rm eff} \lesssim 1/30$ m.‡ Without any loss of generality, this will be considered as a constraint, since the case $\bar{\Delta}_{\rm eff} \gg 1/30$ contradicts the Karmen data [18] and will not provide a realistic solution to the LA. Solving the LA implies, therefore, that $\Delta\sin 2\theta \sim 8\times 10^{-4}$ eV^2/MeV for LSND-like energies $E_\nu \sim$(30–55) MeV. This in turn implies, for solar neutrinos, $\Delta_{\rm eff} \gtrsim 3\times 10^{-3}$ eV^2/MeV (remember the largest solar neutrino energy is three times smaller than the smallest LSND energy), such that $\Delta_{\rm eff} \gg \sqrt{2}G_F N_e$. Therefore, matter effects inside the Sun will be very weak, and the best hope for

†The "dark side" $\pi/4 \leq \theta \leq \pi/2$ cannot be ignored due to standard matter effects [16].

‡The notation $\bar{\Delta}_{\rm eff}$ and $\bar{\theta}_{\rm eff}$ will be used to represent the antineutrino quantities, where V, V_{ex} are replaced by $-V, -V_{ex}$ respectively.

solving the SNP will be to obtain a very large effective mixing angle. This also explains why the adiabatic approximation works very well.

In order to obtain $\sin^2 2\theta_{\rm eff} \sim 1$ one can choose $V \sim \Delta \cos 2\theta$, such that there is an MSW-like resonance at a typical solar neutrino energy $E_\nu = E^*$ between 0–10 MeV. In more detail

$$\sin^2 2\theta_{\rm eff} = \left[1 + \left(\frac{\delta E}{E^* \tan 2\theta}\right)^2\right]^{-1}, \tag{3.9}$$

where $\delta E \equiv E_\nu - E^*$ and E^* is the resonant solar neutrino energy. The energy dependence of the solar neutrino data requires, very generously, that, for $\delta E \sim E^*$, $\sin^2 2\theta_{\rm eff} \gtrsim 0.6$.[§] This translates into $\tan^2 2\theta > 3/2$. It turns out that the CHOOZ bound [19] on $P_{\bar{e}\bar{e}}$ forbids such a choice.

At CHOOZ, $\bar{\Delta}_{\rm eff} \gtrsim 3 \times 10^{-3}$ eV^2/MeV (remember that typical reactor antineutrino energies are of the order of typical solar neutrinos energies), such that $1 - P_{\bar{e}\bar{e}} \sim 1/2 \sin^2 2\bar{\theta}_{\rm eff}$ at the CHOOZ experiment ($L_{\rm CHOOZ} \sim 1000$ m). Assuming that there is a resonance in the solar neutrino sector at some $E_\nu = E^*$,

$$\sin^2 2\bar{\theta}_{\rm eff} = \frac{\tan^2 2\theta}{\tan^2 2\theta + (1 + E_{\bar{\nu}}/E^*)^2}, \tag{3.10}$$

and the bound $\sin^2 2\theta_{\rm eff} < 0.1$ from CHOOZ translates into $\tan^2 \theta < 4/9$, in disagreement with the requirements from the the SNP discussed above.

Next, consider $V = 0$ but $V_{ex} \neq 0$. As before, the LA will constrain $(\bar{\Delta}_{\rm eff} \sin 2\bar{\theta}_{\rm eff})^2 = (\Delta \sin 2\theta - V_{ex})^2 \simeq (8 \times 10^{-4})^2$ eV^4/MeV^2. In the case $|V_{ex}| < \Delta \sin 2\theta$, the survival probability will be very similar to the case of no Ether ($\Delta_{\rm solar} \gg \Delta_{\rm LSND}$), and is therefore uninteresting.

The opposite hypothesis, $|V_{ex}| \gg \Delta \sin 2\theta$ for typical LSND energies invites further investigation. In this case, the LA implies $|V_{ex}| \sim 8 \times 10^{-4}$ eV^2/MeV. If $|V_{ex}| \gg \Delta \sin 2\theta$ also for typical solar neutrino energies, $\sin^2 2\theta_{\rm eff} \sim 1$ for solar neutrinos, which provides a reasonable solution to the SNP. This possibility is, unfortunately, immediately killed by the CHOOZ bound, since $\sin^2 2\bar{\theta}_{\rm eff} \sim 1$ for typical reactor antineutrino energies.

Another possibility, which can be quickly discarded, is the case $V_{ex} + \Delta \sin 2\theta = 0$ and $\Delta \cos 2\theta$ very small for typical solar neutrino energies, such that $\Delta_{\rm eff} \sim \sqrt{2} G_F N_e^0$. In this case, $\bar{\Delta}_{\rm eff} \sim V_{ex}$ is large, such that the CHOOZ bound would be grossly violated, namely, $1 - P_{\bar{e}\bar{e}} \sim 1/2$ at CHOOZ.

Finally, there is the possibility of evoking an “antiresonance” at CHOOZ, namely $\Delta \sin 2\theta - V_{ex} = 0$ for some reactor antineutrino energies $E_{\bar{\nu}} = \bar{E}^*$. In this case, one may hope to obtain maximal effective mixing in the neutrino sector and solve the SNP. In more detail

$$\sin^2 2\bar{\theta}_{\rm eff} = \frac{(\delta E/\bar{E}^*)^2}{(\delta E/\bar{E}^*)^2 + {\rm cotan}^2 2\theta}, \tag{3.11}$$

where $\delta E \equiv E_{\bar{\nu}} - \bar{E}^*$. Note that away from $\bar{E}^*$, the CHOOZ bound still presents a limit for $\tan^2 \theta$. For example, requiring $1 - P_{\bar{e}\bar{e}} < 0.5$ for $\delta E/\bar{E}^* = 1/2$ implies $\tan^2 2\theta < 4/9$.

Under these circumstances, the solar effective angle is

$$\sin^2 2\theta_{\rm eff} = \frac{(1 + E_\nu/\bar{E}^*)^2}{(1 + E_\nu/\bar{E}^*)^2 + {\rm cotan}^2 2\theta}, \tag{3.12}$$

which, in the limit $E_\nu \ll \bar{E}^*$ implies $P_{ee} \gtrsim 0.85$, in disagreement with the solar data.

It worthwhile to comment at this point that it should not come as a surprise that no remotely appropriate fit to all neutrino data can be obtained with either $\Delta m^2, \theta$, and V, or $\Delta m^2, \theta$, and V_{ex} as free parameters: the fit is severely over constrained. It remains, however, to check whether the addition of a fourth free parameter can help significantly. There is some room for optimism, since

[§] Under these circumstances, P_{ee} is constrained to be between 0.5 and 0.7 for the entire solar neutrino energy range. This provides a rather poor fit to the data, but is the best one can hope to achieve.

nonzero V and V_{ex} seem to play significantly different roles in the previous discussions. For example, one may envision a large V_{ex} which can take care of the CHOOZ bound, combined with a small enough θ and a large enough Δm^2 to solve the LA. The SNP may be solved by appropriately choosing V in order to enforce a large effective solar mixing angle, and so on.

An optimal solution was numerically searched by performing a "straw-man fit" to the CHOOZ, solar and LSND data. Explicitly, this was done by requiring that $P_{ee} = 0.4 \pm 0.1$ in ten 1 MeV-wide solar neutrino energy bins (from 0 to 10 MeV), $1 - P_{\bar{e}\bar{e}} = 0 \pm 0.04$ in seven 1 MeV-wide reactor antineutrino energy (from 2 to 9 MeV) bins at CHOOZ, and $P_{\bar{\mu}\bar{e}} = 0.25\% \pm 0.08\%$ in five 5 MeV-wide antineutrino energy bins at LSND (from 30 to 55 MeV). A more detailed fit is beyond the scope of this discussion, but it should be noted that the constraints imposed here are rather mild, such that a realistic fit will probably yield more severe constraints on an Ether solution to both the SNP and LA. The oscillation probabilities obtained at the solar, reactor, and LSND (anti)neutrino energy ranges are depicted in Fig. 1, for one "best fit point:" $\Delta m^2 = 0.01$ eV^2, $\cos 2\theta = 0.6$, $V = 0.001$ eV^2/MeV, and $V_{ex} = 0.001$ eV^2/MeV. Other points which also provide a reasonable fit are very similar, and characterized by $0.0007 \lesssim V_{ex} \lesssim 0.0012$, $0.0001 \lesssim V \lesssim 0.001$, $0.5 \lesssim \cos 2\theta \lesssim 0.7$, $0.005 \lesssim \Delta m^2 \lesssim 0.015$ eV^2.

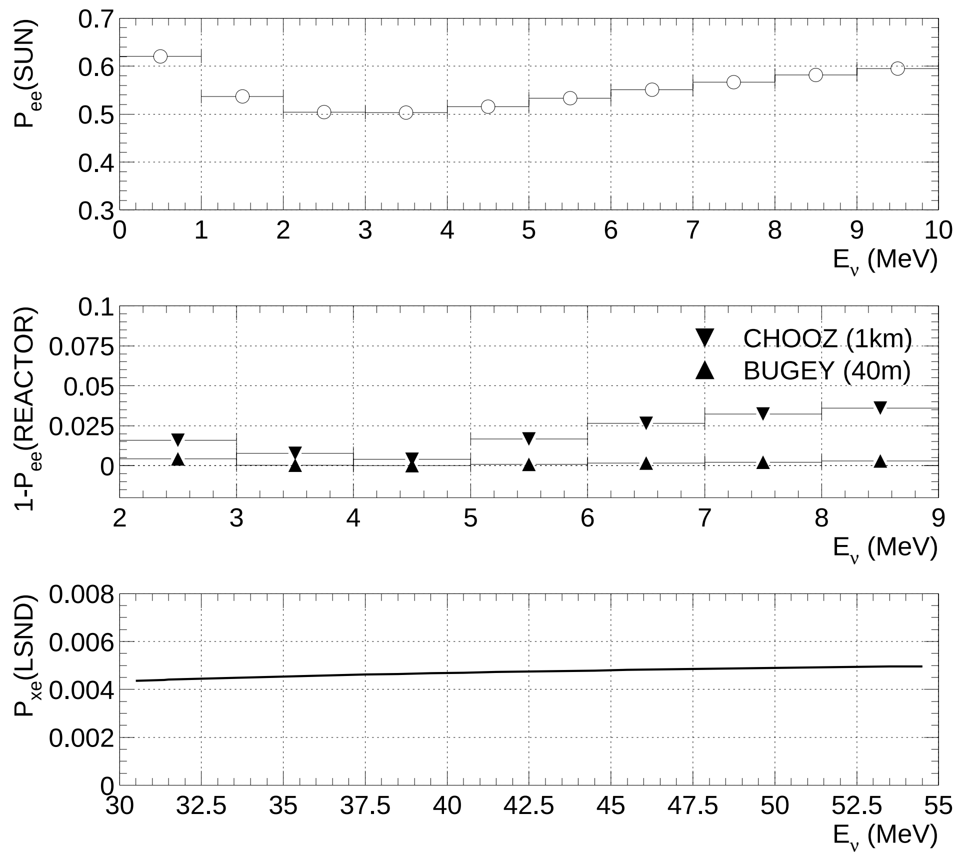

Figure 1: TOP – P_{ee} for solar neutrinos, CENTER – $1 - P_{\bar{e}\bar{e}}$ for reactor antineutrinos (at both the CHOOZ Bugey experiments) and BOTTOM – $P_{\bar{x}\bar{e}} \sim 2 \times P_{\bar{\mu}\bar{e}}$ at the LSND experiment, as a function of the (anti)neutrino energy, for $\Delta m^2 = 0.01$ eV^2, $\cos 2\theta = 0.6$, $V = 0.001$ eV^2/MeV, and $V_{ex} = 0.001$ eV^2/MeV (see text for details).

A few comments are in order. First of all, the result obtained is not altogether inconsistent with the data. As a matter of fact, the result obtained is in good agreement with the reactor constraints, and the LSND data. The Karmen constraints are easily satisfied, given that $\bar{\Delta}_{eff} \ll 1/L$ at both

LSND and Karmen, such that oscillation effects at the Karmen site are suppressed with respect to effects at the LSND experiment by $(30/18)^2$. (remember that $P_{\bar{\mu}\bar{e}} \simeq 0.5 \times P_{\bar{x}\bar{e}}$). The biggest concern rests in the solution to the SNP. The fact that $P_{ee} > 0.5$ in the entire energy range (the reason for this, namely the fact that $\Delta_{\rm eff} \gg \sqrt{2} G_F N_e^0$ has already been addressed in detail), implies that a good fit to the solar data cannot be obtained. For example, the SNO and SuperKamiokande data alone rule out this model at more than the two sigma level.¶ Nonetheless, the energy dependency of P_{ee} obtained for the Ether model considered here is not too different from that obtained for regular two-neutrino oscillations and $\Delta m^2_{\rm solar} >$ few $\times 10^{-4}$ eV^2.

Next, I address the atmospheric neutrino data. For atmospheric (anti)neutrinos, which travel at least 10 km before reaching the, say, SuperKamiokande detector, $L \gg 1/\Delta_{\rm eff}, 1/\bar{\Delta}_{\rm eff}$ assuming that the values of the four parameters $\theta, \Delta m^2, V, V_{ex}$ provide a proper fit to the SNP and the LA. This means that $P_{ee} \simeq 1 - 1/2 \sin^2 2\theta_{\rm eff}$. Furthermore, because $\Delta_{\rm atm} \lesssim 10^{-5}$ eV^2/MeV $\ll V, V_{ex}$, $\sin^2\theta_{\rm eff} \simeq (V_{ex})^2/((V_{ex})^2 + (V)^2)$. Given the range of parameters delimited above, one obtains

$$0.75 \lesssim P_{ee} \simeq P_{\bar{e}\bar{e}} \lesssim 0.5, \tag{3.13}$$

for all E_ν and all L. Such a possibility is certainly not a good fit to the atmospheric neutrino data, which clearly prefers $P_{ee} \simeq P_{\bar{e}\bar{e}} \simeq 1$. In order to be able to make a definitive statement, however, a full three neutrino analysis of the atmospheric data including the Ether term is required. Nonetheless, there is a hint that the Ether hypothesis is strongly disfavored if one considers the current constraint on $|U_{e3}|^2$ from the ANP [21]. A realistic analysis may provide even stronger constraints, given that the value of $P_{ee}, P_{\bar{e}\bar{e}}$ above are energy independent, and should also modify the measured ν_μ-flux distributions significantly (given that $1 - P_{ee} \sim 0.5 P_{\mu e}$).

Finally, the most stringent constraints come from old $\bar{\nu}_\mu \to \bar{\nu}_e$ searches [22].‖. Similar to atmospheric neutrinos, the neutrinos in these experiments are high energy and the baseline is long, such that $0.25 \lesssim P_{xe} \sim P_{\bar{x}\bar{e}} \lesssim 0.5$. The result of [22], namely $P_{\bar{\mu}\bar{e}} < 6.5 \times 10^{-3}$, is in gross disagreement with the "best fit" expectations quoted above.

In summary, it is fair to say that the presence of an Ether potential cannot accommodate the current neutrino data, at least when the Ether terms affect only the $\nu_e \leftrightarrow \nu_x$-sector ($\nu_x$ is a linear combination of ν_μ, ν_τ). While a good fit to the LA and the reactor data can be obtained, only a marginal solution to the SNP exists, and there are further constraints from the atmospheric data and older searches for $\bar{\nu}\mu$ oscillations. However, the fact that one cannot fit all the data should not come as a surprise. The most important reason for this expectation is that the Ether term serves as an effective potential, and not an effective mass. This implies that a) the standard L/E behavior of the survival probabilities will be severely modified, b) the effective mixing angle will vary substantially with energy and c) standard matter effects are altered. Indeed, the fact that the SNP and the LA can be marginally reconciled without violating the CHOOZ bound may come as a bigger surprise (at least to me)!

An important question is whether a full three neutrino fit could be more successful. Such a fit would contain eleven free parameters (two mass-squared differences, three mixing angles, one complex Dirac phase and five Ether-terms) and is certainly beyond the scope of this discussion. While there are enough new free parameters (which should render performing such a fit very challenging), it is worthwhile to comment that many features of the atmospheric data, such as the peculiar L/E of the ν_μ flux should prove to be a serious challenge to the oscillations in the Ether, indicating that such a fit will encounter challenges which are not too dissimilar from the ones faced here. I believe that obtaining a successful fit to all the data with a three-neutrino is rather improbable, but, perhaps, not impossible.

¶See [14] for a detailed discussion. The best possible fit (already excluded at more than the 2 sigma level) would be obtained if the Standard Solar Model prediction for the ^{8}B solar neutrino flux [20] was off by a factor of 2.

‖I thank Alessandro Strumia for pointing this out. The fact that severe constraints should be obtained from these experiments was first alluded to in [23].

4 Summary and Discussions

CPT violation implies, necessarily, violation of Lorentz invariance and/or Locality. Under certain circumstances, CPT violation requires a reinterpretation of the Quantum Field Theoretical formalism which is used to describe, extremely successfully, all short distance physics to date.

It has been pointed out that if the neutrinos and antineutrinos had different masses (CPT violation), all neutrino puzzles could be solved without the addition of extra light degrees of freedom to the standard model. This hypothesis seems to violate both Lorentz invariance and Locality, and renders a Quantum Field theoretical description of the neutrinos (including loop-effects, time-evolution, etc) rather cumbersome.

Here, I have considered a formalism for CPT violation [9, 12] which can be treated self consistently within Quantum Field Theory (it look like "standard" effective field theory) by adding a few effective Lorentz invariant-violating operator (Ether potentials). It turns out, however, that one cannot obtain a set of parameters which will satisfy the solar neutrino data, the atmospheric neutrino data, the LSND data, and the reactor data at the same time, at least within a two-flavor analysis. I tried to argued that, contrary to previous claims [8], one should at least suspect that the existence of Ether terms is insufficient to accommodate all the neutrino data. The most interesting feature discussed here is, perhaps, the fact that a good fit can almost be obtained if both diagonal and, more importantly, off-diagonal Ether potentials are present. One of the big barriers one is forced to face is the fact that, for solar neutrinos, the electron neutrino survival probability is always greater than one half, in contradiction with the current solar neutrino data (*e.g.,* SuperKamiokande and SNO). If it turns out that the solar data definitively *requires* $P_{ee} < 0.5$ (at a very high confidence level) for a finite energy range, the Ether solution would be unambiguously ruled out. This may very well be achieve after the new SNO results on the neutral current cross-section and the day-night effect are released.

Constraints on V and V_{ex} (as defined in the previous section) are, of course, possible to obtain outside the realm of neutrino oscillations. The authors of [24] already point out that, through loops, one can severely constraint V_{ee}.** Since oscillation signatures only depend on $V_{ee} - V_{\mu\mu}$, this strong bound is irrelevant if one allows $V_{ee} \ll V_{\mu\mu}$. On the other hand, if the Ether terms were to be written in $SU(2)_L \times U(1)_Y$ invariant forms, very severe tree-level constraints from the charged lepton sector would probably render the model useless as far as neutrino oscillation phenomenology is concerned.

Constraints on the off-diagonal V_{ex} and on the second generation $V_{\mu\mu}$ are expected to be much weaker, and the best constraints will come from the neutrino oscillations experiments themselves. For example, from the discussions in the previous section, the LA already constraints $|V|, |V_{ex}| \lesssim 10^{-3}$ eV^2/MeV $= 10^{-18}$ GeV. Future neutrino experiments including KamLAND ([25] for a detailed discussion), Borexino and long baseline neutrino experiments (for a detailed discussion, see [17]) can push the bounds on $V_{\alpha\beta}$ by many orders of magnitude. For example, if it turns out that strong solar matter effects are required to solve the SNP, one would be force to constraint $|V|, |V_{ex}| \lesssim 10^{-5}$ eV^2/MeV $= 10^{-20}$ GeV, while if Borexino observes seasonal variations, their data will be consistent with $\Delta m^2/2E_\nu \lesssim 10^{-9}$ eV^2/MeV $= 10^{-24}$ GeV [26], implying $|V|, |V_{ex}| \lesssim 10^{-24}$ GeV.

Acknowledgements

I am happy to thank Gabriela Barenboim, John Beacom, and Boris Kayser for suggestions and comments on the manuscript. I also thank Alessandro Strumia for very useful comments. This work was supported by Fermilab, which is operated by the URA under DOE contract No. DE-AC02-76CH03000.

**[24] considers a "seesaw"-like origin for the neutrino masses and the CPT violating operators, such that some "translation" to the formalism used here is required in order to read off the bound on V_{ee}.

References

[1] Homestake Coll. (B.T. Cleveland *et al.*), Astrophys. J. **496**, 505 (1998); GALLEX Coll. (W. Hampel *et al.*), Phys. Lett. **B447**, 127 (1999); Y. Suzuki, for the Super-Kamiokande Coll., Nucl. Phys. **B** (Proc. Suppl.) **91**, 29 (2001); V.N. Gavrin, for the SAGE Coll., Nucl. Phys. **B** (Proc. Suppl.) **91**, 36 (2001); E. Bellotti, for the GNO Coll., Nucl. Phys. **B** (Proc. Suppl.) **91**, 44 (2001); Super-Kamiokande Coll. (S. Fukuda *et al.*), hep-ex/0103032; SNO Coll. (Q. R. Ahmad *et al.*), Phys. Rev. Lett. **87**, 071301 (2001).

[2] NUSEX Coll. (M. Aglietta *et al.*), Europhys. Lett., **8**, 611 (1989); R. Becker-Szendy *et al.,* Phys. Rev. **D46**, 3720 (1992); Kamiokande Coll. (Y. Hirata *et al.*), Phys. Lett. **B280**, 146 (1992); Kamiokande Coll. (Y. Fukuda *et al.*), Phys. Lett. **B335**, 237 (1994); Frejus Coll. (K. Daum *et al.*), Z. Phys. **C66**, 417 (1995); Super-Kamiokande Coll. (Y. Fukuda *et al.*), Phys. Rev. Lett. **81**, 1562 (1998); W.A. Mann, for the Soudan 2 Coll., Nucl. Phys. **B** (Proc. Suppl.) **91**, 134 (2001); B.C. Barish, for the MACRO Coll., Nucl. Phys. **B** (Proc. Suppl.) **91**, 141 (2001).

[3] LSND Coll. (C. Athanassopoulos *et al.*), Phys. Rev. Lett. **75**, 2650 (1995); **77**, 3082 (1996); **81**, 1774 (1998); W.C. Louis for the LSND Coll., Nucl. Phys. **B** (Proc. Suppl.) **91**, 198 (2001); LSND Coll. (A. Aguilar *et al.*), Phys. Rev. **D 64**, 112007 (2001).

[4] G. Barenboim *et al.,* hep-ph/0108199.

[5] H. Murayama and T. Yanagida, Phys. Lett. **B520**, 263 (2001).

[6] See, for example, R. Streater and A.S. Wightman, "PCT, Spin and Statistics, and All That," (Benjamin, New York, 1964); R. Jost, "The General Theory of Quantized Fields," (American Mathematical Society, Providence, 1965).

[7] O.W. Greenberg, hep-ph/0201258.

[8] G. Barenboim, L. Borissov and J. Lykken, hep-ph/0201080.

[9] S. R. Coleman and S. L. Glashow, Phys. Rev. **D 59**, 116008 (1999); Phys. Lett. **B405**, 249 (1997).

[10] J. Busenitz]it et al., "Proposal for US Participation in KamLAND," March 1999 (unpublished). May be downloaded from `http://bfk0.lbl.gov/kamland/`.

[11] G. Ranucci for the Borexino Coll., Nucl. Phys. B (Proc. Suppl.) **91**, 58 (2001).

[12] D. Colladay and V. A. Kostelecky, Phys. Rev. **D 55**, 6760 (1997).

[13] A. Bandyopadhyay *et al.,* hep-ph/0106264; P. Creminelli, G. Signorelli, and A. Strumia, hep-ph/0102234 – updated version (July 2001); P.I. Krastev and A.Yu. Smirnov, hep-ph/0108177. See also [21] for a review and an extensive list of references.

[14] G. L. Fogli *et al.*,, Phys. Rev. **D 64**, 093007 (2001); plus the addendum at hep-ph/0203138.

[15] A. de Gouvêa, hep-ph/0109150.

[16] A. de Gouvêa, A. Friedland, and H. Murayama, *Phys. Lett* **B490**, 125 (2000).

[17] V. D. Barger *et al.,* Phys. Rev. Lett. **85**, 5055 (2000).

[18] Karmen Coll. (B. Armbruster *et al.*), hep-ex/0203021.

[19] Chooz Coll., (M. Apollonio *et al.*), *Phys. Lett.* **B466**, 415 (1999).

[20] J. N. Bahcall, M. H. Pinsonneault and S. Basu, Astrophys. J. **555**, 990 (2001).

[21] M. C. Gonzalez-Garcia and Y. Nir, hep-ph/0202058, and many references therein.

[22] see, for example, G. N. Taylor *et al.*, Phys. Rev. **D 28**, 2705 (1983).

[23] A. Strumia, hep-ph/0201134.

[24] I. Mocioiu and M. Pospelov, hep-ph/0202160.

[25] J. N. Bahcall, V. Barger and D. Marfatia, hep-ph/0201211.

[26] A. de Gouvêa, A. Friedland and H. Murayama, Phys. Rev. **D 60**, 093011 (1999).