Neutrino oscillations along the Earth to probe flavor parameters: a *NeuWorld*

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**Abstract**

On 2010 MINOS experiment was showing an hint of possible different mass splitting and mixing angles for neutrinos and anti-neutrinos, suggesting a charge-parity-time (CPT) violation in the lepton sector; later on last year 2012 a second result from MINOS showed a reduced discrepancy between the two set of parameters, nearly compatible with no CPT violation. We proposed an experiment for more precise estimation of neutrino and $\nu_{\tau}$ oscillation parameters being useful not only for a complete discrimination for CPT scenarios, but also for mass hierarchy and $\theta_{13}$ determination, and mostly for the first oscillated detection of tau, $\nu_{\tau}$ and $\bar{\nu}_{\tau}$, neutrinos. Indeed, the last a few years of OPERA activity on the appearance of a $\tau$ lepton still has not been probed convincingly. Moreover atmospheric anisotropy in muon neutrino spectra in IceCube DeepCore, at $\approx 10$ GeV, can hardly reveal asymmetry in the $\nu_{\mu} - \bar{\nu}_{\mu}$ oscillation parameters nor the tau and anti tau appearance. We show an experiment, (the longest baseline neutrino oscillation test available by crossing most of Earth’s diameter, a *NeuWorld*), that may improve the oscillation measurement and disentangle at best any hypothetical CPT violation while testing $\tau$ and $\bar{\tau}$ appearance at the same time of the $\nu_{\mu} - \bar{\nu}_{\mu}$ disappearance correlated. The experiment use a neutrino beam crossing the Earth, within an OPERA-like experiment from CERN (or Fermilab), in the direction of the IceCube DeepCore detector at the South Pole. Such a tuned beaming and its detection may lead to a strong signature of neutrino muon-tau mixing (nearly one $\bar{\tau}$ or two $\tau$ a day, with $10\sigma$ a year), even for an one per-cent OPERA-like experiment.

**Keywords:**

1. Introduction

The MINOS 2010 observations seemed to imply (or now at least to marginally hint) a different antineutrino mass splitting with respect to well known neutrino one, leading to a possible CPT violation. Even a marginal neutrino anti-neutrino mass difference may open new roads in our particle physics understanding. This CPT violation might indicate a very peculiar role of neutral leptons in matter/anti-matter genesis, and it may address unsolved lepton-baryon-generation open puzzle, related to cosmological mysteries. Consequently such a tiny CPT violation, if confirmed, might become one of the main (amazing) discovery of the century: therefore we inquire how at best CPT violation may be observed. In order to do that we proposed two ways: (1) exploiting current and coming soon atmospheric data from IceCube DeepCore detector, and (2) considering a completely new neutrino oscillation baseline. Such experiment should beam neutrinos across the whole Earth: *NeuWorld*, and it is almost ready since both accelerator and detector already exist suitable for that. Only a new tunnel, Opera-like, is necessary.

2. A road map to disentangle mixing flavors

We considered first the ongoing experiment based on atmospheric neutrino signal in DeepCore that may be a benchmark for CPT scenario disentangling; we underline that the smeared muon track energy measure and the angular resolution can confuse any tiny CPT anisotropy in Deep Core spectra (Fig 1); such smeared anisotropies might be not clearly detected by present at-
commercial neutrino records in Deep Core. Only a negligible difference would rise in the low channel muon tracks by allowable CPT violation, as shown in Fig. 1. On the contrary the common muon disappearance (as the SK observation) will be anyway observable.

Therefore we focus here on a future possible ad-hoc Very Long Baseline experiment able to sharply confirm even tiny CPT violation in a very short time and in an accurate way. We studied the appearance of muon neutrino by $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ oscillations, in the energy-distance range where CPT conserved oscillation is almost vanishing, while CPT violated oscillation is (partially) allowed, based on the experimental parameters determined by MINOS. By doing this we will be able also to test with great accuracy the $\nu_\mu \to \nu_\tau$, and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ mixing, leading also to a very precise estimate of their mixing parameters that may shed also light to a possibly hidden symmetry unwritten into a tuned value: $\sin(2\theta_{23}) \approx 1$.

We performed an estimation for other experiment such as OPERA, at Gran Sasso, for calibration. A common shortcoming of most baseline experiments (thousand or hundreds km $\nu$ flight) is the very un-efficient flavour conversion probability and the usual low neutrino energy. The higher the energy, the larger the distance needed to complete a mixing oscillation, but also the better the beaming, (because of the higher Lorentz factor of pion decay), as well as the larger the neutrino cross-section. Incidentally the approximate beaming solid angle shrinks by a factor proportional to $E^3_{\nu}$, and the neutrino-matter cross-section grows as $E_{\nu}$, providing a global signal enhancement amplified by a factor proportional to $\sim E^3_{\nu}$. Therefore a long-baseline experiment for instance as in our NeuWorld[2] experiment at 22 GeV, may play a better role (8000 times better than 1 GeV experiment) to define oscillation parameters. Moreover the dilution factor due to the much greater distance from CERN of DeepCore than OPERA [1], a factor $\approx 240$, is widely compensated by the detector mass ratio (DeepCore versus OPERA), at least by a factor $\approx 4800$, implying a benefit of a factor $\approx 20$. In addition the larger distance in the NeuWorld[2] baseline offers a complete $\nu_\mu \leftrightarrow \nu_\tau$ conversion with respect to 1.5% of OPERA, providing a further gain of an additional factor $\approx 60$. All together the advantages of a long baseline experiment with DeepCore (respect to OPERA) in tau appearance, is a factor of about or above 2400; moreover all the born $\tau$ (within the limited 4.8 Mton DeepCore) will be observable (contrary to OPERA), leading to an efficiency ratio $15 : 1$ for NeuWorld, leading to an exceptional ratio 36000 between NeuWorld and OPERA [1] in testing tau appearance. One tau a day in our scenario even for just at 1% OPERA size NeuWorld experiment versus one rare tau a year in present OPERA experiment (see more precise details in next Tables). We remind that we are considering half detection volume respect the one claimed, just for prudential reasons [6, 7].

Our main proposal therefore stands for building a baseline from CERN (or FNAL) to IceCube DeepCore detector, at $E_{\nu} \sim 20$ GeV, with more than 4 MegaTon detection mass. SuperKamiokande detector was also considered, but found to be not enough in terms of signal intensity, in comparison to DeepCore.

Therefore we estimated in detail, for each source (CERN or FNAL), for each Proton On Target source flux (and its secondary neutrino flux) and for each detector distance (SK or IceCube), the results (muons or tau events) by a chain of neutrino-signal values source-propagation-flavor mixing and oscillation in Earth, the detection rate in volume inside or outside the detector.
Each value or formula is deeply correlated to the previous one, leading to a realistic estimate of muon or anti-muon signals (as well as tau-anti tau), designed at best to disentangle the hypothetical CPT asymmetry as well as to fix with high accuracy muon-tau flavor mixing parameters.

3. NeuWorld: Neutrino events in longest baselines

In figure 2 we show muon neutrino oscillation probability versus neutrino energy, for the two set of parameters, conserving and violating CPT, that is assuming the same parameters for both $\nu \rightarrow \bar{\nu}$ (under CPT conserved case) and different parameters between $\nu$ and $\bar{\nu}$ (under CPT violated case). It is clearly visible that in the eventual CPT violated scenario, a different oscillation for $\nu_\mu$ and $\bar{\nu}_\mu$ would result, leading to a discrepancy in the event number, while this would not be for usual symmetry between matter and anti-matter. Therefore we suggest this new $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance experiment, and propose various longest baselines, for which both source and detector are already available. All considered baselines are listed in table 1.

The method of estimating the beaming and detection of neutrinos to detectors (DeepCore or SuperKamiokande) is based on a chain of correlated evaluations that we used and calibrated with known experiments: OPERA and MINOS. By evaluating the chord distance and the appropriate energy enhancing neutrino oscillation, we find $\nu_\tau$ event rate as would be no oscillation, in comparison to known rates in OPERA for instance, using the same p.o.t. number (table 1). The energy is chosen as to maximize $\nu_\tau$, disappearance, so that any event different $\nu_\tau$ oscillation probability (in CPT violated case) would be clearly visible over a nearly null background. We do remind that because accurate timing in sending neutrino bunches along the Earth one may easily cancel any rare upward atmospheric neutrino noise, also because of the selected narrow angle arrival direction.

We always take in consideration the flavor neutrino mixing within the Earth, keeping care of the exact step by step variability of the inner matter density. At energies $\geq 20$ GeV, nevertheless, the flavor mixing along the Earth diameter is not very much different from the vacuum case, but we did take into account of it.

In table 2 we consider the primary bunch bending and tunnel parameters, for a 1 Tesla magnetic field curving a pion beam at nearly 50 GeV energy. In the most economic version the whole tunnel arc with the rectilinear sector length will be less than 200 m underground. This tunnel cost is the only expenses needed to invest to achieve a the NeuWorld experiment. Detectors (Deep Core) and accelerators (CERN or FNAL) already exist.

In figure 3 it is shown how oscillation probability is averaged by a non-monochromatic ($\Delta E/E = 20\%$) neutrino beam. The presence of such energy smearing increases the noise and reduces the signal significance. This severe noise is usually ignored by most of the other author papers. However, as discussed in the following tables, the event rate in the worst 1% OPERA-like experiment may lead to a remarkable $\sigma$ signal detection of any tiny (MINOS 2012) hypothetical CPT violation within a year of detection.

In table 3 we take in account the averaged oscillation probability and obtain the resulting event for $\nu_\mu$ and $\bar{\nu}_\mu$: the latter $\bar{\nu}_\mu$ is described both for conserved or violated CPT scenarios. These events are compared to a OPERA-like experiment at 100% (decay length and neutrino flux), while in table 4 it is shown a severe economic reduction 1% because a 5% shorter pion decay length and additional 20% due to considering a lower $\nu_\mu$ intensity flux, since our proposed beam select pion flux by a spectrometer energy filter while bending the bunch.

The (preliminary) correlated parameter map derived by a year of recording (in a minimal 1% OPERA beaming experiment) is shown in Figure 4.

We also underline the $\nu_\tau$ appearance, so that our experiment NeuWorld has another important return: this will be able to detect nearly 2 $\tau$ a day, or 1 $\bar{\tau}$ as seen in table 5 and 6. The noise of Neutral Current events was considered as background, leading nevertheless to a $14 \sigma$ for tau appearance and $10 \sigma$ for anti-tau appearance.

| Baseline         | Distance (km) | $E_0$ (GeV) | $|\Delta E|/E$ | Mass detector | $N_{\text{TOF}}^\text{neu}$ (no osc) |
|------------------|---------------|-------------|-------------|---------------|----------------------------------|
| CERN-OPERA       | $L = 712$    | 17          | 1           | 1.2           | 9947                             |
| CERN-SK          | $L^\prime = 9377$ | 15.8       | 142.5       | 22.9          | 324                              |
| Fermilab-UK      | $L^\prime = 9140$ | 16.5       | 153.9       | 22.8          | 341                              |
| CERN-ICEcube     | $L^\prime = 11812$ | 21.8       | 200.4       | 4000          | 95345                            |
| Fermilab-ICEcube | $L^\prime = 11625$ | 21.4       | 252.1       | 4000          | 99091                            |

Table 1: Source detector distances, tuned energies, flux dilution, event rate, in comparison with the OPERA baseline.

4. Conclusion

Our recent proposal, NeuWorld experiment [2] shows the estimated $\nu_\mu$, $\nu_\tau$ event rates (and the same for the anti-particles) for two main neutrino baselines and configurations (CERN (or Fermilab) to ICECUBE); the experiment is offering a high rate of detection of muon dis-
between tau-neutrino and muon neutrino, event rates for tau and anti-
tau-neutrino in detector, conversion probabilities in matter, cross section ratio
case. Estimated total events of charged current muon neutrino interac-
tions. Table 4: Muon neutrino and anti-neutrino survival probability (P_{\nu_{\mu}}
and P_{\bar{\nu}_{\mu}}). There is a difference due to a slight asymmetry in the MSW
term for matter effect; moreover such a discrepancy between matter and anti-matter is negligible in our energy window of interest.
The FNAL-SK and FNAL-IceCube oscillations are very comparable
to those from CERN because of very similar distances. Note that while crossing the Earth here and later we did not consider (as most other authors did) only the average density of Earth (respectively, ρ = 4.5gcm^{-3} for "near" SK; ρ = 7.2gcm^{-3} for "far" IceCube DeepCore), but the exact variable matter profile. Nevertheless, the vacuum and matter cases, as shown in figure, do not differ relevantly for energies higher than 10 GeV.

Table 3: ντ and νµ appearance: event rate in conserved and in violated
CPT parameters (100% tunnel length comparable with OPERA). The
events are relative to one year data taking, as they would be with-
out neutrino oscillation. From the first column: the total number of ντ
and νµ events born inside detector and those whose track starts outside
detector; survival probability for ντ and νµ under 20% energy uncer-
tainty; final number of ντ and νµ events for the two CPT scenario.

Table 4: ντ and νµ event rates considering reduced size experiment,
and $\frac{E}{\rho}$ = 20% energy spread. It is shown the very economic setup
where event rate is reduced to 1%, having considered 5% decay tunnel length, and 20% π flux intensity in NeuWorld experiment.

Table 5: Tau-AntiTau neutrinos in matter by CPT conserved-violated
case. Estimated total events of charged current muon neutrino interac-
tion in detector, conversion probabilities in matter, cross section ratio
between tau-neutrino and muon neutrino, event rates for tau and anti-
tau neutrino (last with both conserved and violated CPT-symmetry),
near and noise events by Neutral Current neutrino interactions. Note that
the absence of τ or $\bar{\tau}$ appearance would lead to less than half of the
event showering rate in last columns.

appearance in any MINOS like CPT violation scenario,
as well as a sharp probe of the appearance of many τ and $\bar{\tau}$: at least two or one at a day. This NeuWorld experiment may lead also to an improvement of many neutrino oscillation parameter measure [2] not discussed here, as the neutrino mass hierarchy. Such up-going neutrino beam signals in DeepCore and SuperK is completely noise free from any atmospheric neutrino ones, since the clock and packet time-windows of the sent bunches is narrow and the directionality is also very selective. The NeuWorld experiment is a very promising, being a very low cost one while at once o
Figure 3: Averaged oscillation and survival probability, showing the average conversion smeared by neutrino energy spectra at $\frac{\Delta E}{E} = \pm 20\%$. The survival probability is less sharp than in the monochromatic scenario, however, as shown in Table 4, the event rate even in the framework of a minimal 1% OPERA-like NeuWorld experiment allows us to detect any eventual CPT violation with 6.1σ signature in one year.

just the missing tool.

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Figure 4: Neutrino and anti-neutrino muon oscillation probability in $\text{sin}^2(2\theta_{23}) = 1$ and $\Delta m^2 = (2.35^{+0.11}_{-0.08}) \times 10^{-3}$ eV$^2$ as in old data by MINOS and SK. Also the old $\bar{\nu}_\mu$ oscillation probability into $\bar{\nu}_\tau$ CPT violated parameters was $\Delta \mathcal{M}^2_{23} = (3.36^{+0.45}_{-0.40}) \times 10^{-3}$ eV$^2$ and $\text{sin}^2(2\theta_{23}) = 0.86 \pm 0.11$. On the contrary, the recent parameters are more comparable with the CPT conserved ones $\Delta \mathcal{M}^2_{23} = 2.62^{+0.32}_{-0.28} \times 10^{-3}$ eV$^2$, $\text{sin}^2(2\theta_{23}) = 0.945$. The early MINOS discordance was about 2.5 sigma, but the most recent one is within one sigma consistent with the CPT conserved case. Our beaming across the Earth might reach a discrimination described somehow by the inner smaller ellipses, whose extension at 6 sigma may disentangle even last eventual MINOS tiny CPT discordance.