Atmospheric neutrino oscillations and tau neutrinos in ice

Gerardo Giordano[1], Olga Mena[2], Irina Mocioiu[1]
[1]*Department of Physics, Pennsylvania State University, University Park, PA 16802, USA and*
[2] *Instituto de Física Corpuscular, IFIC, CSIC and Universidad de Valencia, Spain*

(Dated: April 21, 2010)

The main goal of the IceCube Deep Core Array is to search for neutrinos of astrophysical origins. Atmospheric neutrinos are commonly considered as a background for these searches. We show here that cascade measurements in the Ice Cube Deep Core Array can provide strong evidence for tau neutrino appearance in atmospheric neutrino oscillations. A careful study of these tau neutrinos is crucial, since they constitute an irreducible background for astrophysical neutrino detection.

PACS numbers: 14.60.Pq

I. INTRODUCTION

Over the last decade, a large number of experiments of different types have provided strong evidence for neutrino oscillations and thus for physics beyond the Standard Model, see Ref. [1] and references therein.

Cosmic ray interactions in the atmosphere give a natural beam of neutrinos. These atmospheric neutrinos in the GeV range have been used by the Super-Kamiokande (SK) detector to provide evidence for neutrino oscillations [2]. The large size of neutrino telescopes such as AMANDA, IceCube and KM3NeT makes possible the detection of a large number of atmospheric neutrino events with a higher energy threshold, ~ 100 GeV, even though the neutrino flux decreases rapidly with energy ($\sim E_\nu^{-3}$). Built to detect neutrinos from astrophysical sources, or from the decay of Weakly Interacting Massive Particles (WIMPs) annihilations [3], at the high detection threshold energies of these ice/water Cherenkov detectors, neutrino oscillation effects would be small.

Recently, a low energy extension of the IceCube detector, the Ice Cube Deep Core array (ICDC) has been proposed and deployed [4]. It consists of six densely instrumented strings (7 m spacing among optical modules) located in the deep center region of the IceCube detector plus the seven nearest standard IceCube strings. Its goal is to significantly improve the atmospheric muon rejection and to extend the IceCube neutrino detection capabilities in the low energy domain, down to muon or cascade energies as low as 5 GeV. The instrumented volume is 15 Mton. Such a low threshold array buried deep inside IceCube will open up a new energy window on the universe. It will search for neutrinos from sources in the Southern hemisphere, in particular, from the galactic center region, as well as for neutrinos from WIMP annihilation, as originally motivated. In [5] we have proposed neutrino oscillation physics as a further motivation for building such an array. In particular, we have analyzed the sensitivity of ICDC to the neutrino mass hierarchy. ICDC can detect up to $100,000$ atmospheric neutrino events per year, orders of magnitude beyond the present data sample, providing rich opportunities for detailed oscillation studies. In the same spirit of Ref. [5], we concentrate here on the neutrino oscillation analysis in ICDC, focusing now on the cascade signal. By exploiting the cascade channel, ICDC could firstly provide strong evidence for tau neutrino appearance from oscillations of atmospheric neutrinos, greatly improving previous SK results on tau neutrino appearance evidence [6].

Section II reviews briefly our present knowledge of the neutrino oscillation parameters as well as their expected errors from near future facilities. We then describe the cascade analysis details, presenting our main results in section III.

II. NEUTRINO OSCILLATIONS AND CASCADES IN ICDC

Neutrino data from solar, atmospheric, reactor and accelerator experiments is well understood in terms of three-flavor neutrino oscillations. Two Δm^2 values and two (large) mixing angles are well determined, while the third mixing angle is limited to be very small. The CP-violating phase (δ) is completely unconstrained. In addition, the sign of Δm^2_{31} is also unknown.

The best fit oscillation parameter values obtained from present data are [7]:

$$|\Delta m^2_{31}| = 2.5 \times 10^{-3}\mathrm{eV}^2 \tag{1}$$
$$\Delta m^2_{21} = 7.6 \times 10^{-5}\mathrm{eV}^2 \tag{2}$$
$$\sin^2 2\theta_{23} = 1 \tag{3}$$
$$\tan^2 \theta_{12} = 0.47 \tag{4}$$

and $\sin^2 2\theta_{13} \leq 0.15$ for $\Delta m^2_{31} = 2.5 \times 10^{-3}\mathrm{eV}^2$. Notice that an extra unknown in the neutrino oscillation scenario is the octant in which θ_{23} lies, if $\sin^2 2\theta_{23} \neq 1$. This has been dubbed in the literature as the θ_{23} octant ambiguity.

In the near future, long baseline experiments like MINOS [8] will improve the current precision on Δm^2_{31} and possibly discover a non-zero value of θ_{13}, if this is close to the present upper limit. In a few years, reactor experiments like DoubleChooz [9], RENO [10] and DayaBay [11] will provide improved sensitivity to θ_{13}. This information can be used as input in our analysis, reducing some of the parameter uncertainties.

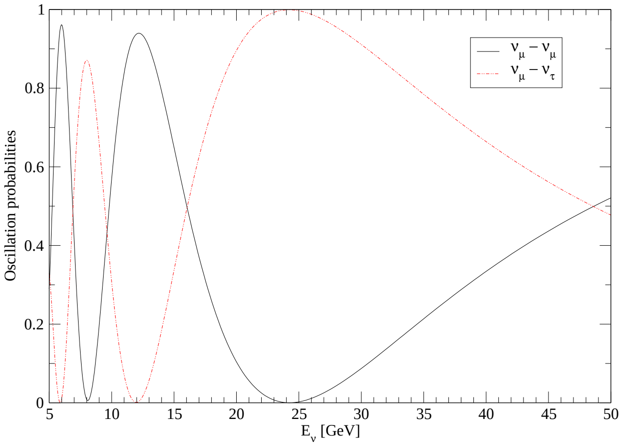

FIG. 1: ν_μ survival probability and $\nu_\mu \to \nu_\tau$ oscillation probability as a function of the neutrino energy (in GeV), assuming upward going neutrinos and $\sin^2 2\theta_{13} = 0.1$.

In the past, atmospheric neutrinos in the SK detector have provided evidence for neutrino oscillations and the first measurements of $|\Delta m^2_{31}|$ and $\sin^2 2\theta_{23}$ [2], therefore providing compelling evidence for neutrino oscillations versus other more exotic phenomena [12]. While facing more systematics than accelerator/reactor experiments due to the uncertainties in the (natural source) neutrino fluxes, atmospheric neutrinos provide great opportunities for exploring oscillation physics due to the large range of energies and pathlengths that they span. The ICDC detector will collect a data sample which is a few orders of magnitude larger than the SK experiment and can also measure energy and directional information, such that many of the systematic errors associated with unknown normalizations of fluxes, cross-sections, etc. can be much better understood by using the data itself.

The IceCube detector and its Deep Core extension are optimized for detecting muon tracks from the charged current interactions of ν_μ. It is, however, possible to also detect cascades [13]. While these type of events no longer provide directional information, their energy can be measured quite precisely. We analyze here the cascade events in the ICDC array. There are several contributions to the cascade signal: charged current interactions of ν_e, neutral current interactions of all neutrino flavors and electromagnetic and hadronic decays of tau leptons produced in charged current interactions of ν_τ. There are several important observations which suggest that the ν_τ signal can be significant and can provide evidence for ν_τ appearance from oscillations of ν_μ:

- First, the atmospheric electron neutrino and electron antineutrino fluxes at the relevant energies are significantly lower than the muon neutrino flux, such that the ν_e charged current interactions do not completely overwhelm the event rate.
- In addition, the energy range covered by ICDC corresponds to a maximum of $\nu_\mu \to \nu_\tau$ oscillations (minimum of ν_μ survival), as can be noticed from Fig. 1.

The large flux of atmospheric muon neutrinos can thus lead to a large flux of tau neutrinos. This has already been noted in [5], where it was shown that $\nu_\mu \to \nu_\tau \to \tau \to \mu$ provides a non-negligible contribution to the muon track rate. It is also important to note that, unlike for the SK detector, which is sensitive at much lower energies, tau threshold production effects are relatively small, only affecting the lowest energy events detected by ICDC.

We investigate the neutrino energy range between 10 GeV and 100 GeV, assuming bins of 5 GeV width in the observable energy. Cascades have very little directional information, especially at these low energies, so we integrate over all upward going directions [19]. The downward going neutrinos are largely unaffected by oscillations, so they can be used for determining the atmospheric neutrino flux and thus the contribution of the ν_e charged current interactions to the overall cascade rate. In our numerical calculations we have taken into account full three flavor oscillations. It is however straightforward to see that solar parameters do not play an important role in the analysis due to the rather high energy threshold of ICDC. Also, θ_{13} effects, while in principle observable for values of θ_{13} close to the present bound, do not affect any conclusions regarding ν_τ rates, which are determined by the (maximal) atmospheric mixing angle θ_{23}.

The spectrum of ν_e induced events as a function of observable energy is given by:

$$\frac{\mathrm{d}N_e}{\mathrm{d}E_{obs}} = 2\pi n_T t \int d\cos\theta \; V \; \sigma^{\mathrm{CC}}_{(\nu_e)}(E_\nu) \left(\frac{d\phi_{\nu_e}(\theta, E_\nu)}{dE_\nu d\Omega} \; P_{\nu_e \to \nu_e}(E_\nu, \theta) + \frac{d\phi_{\nu_\mu}(\theta, E_\nu)}{dE_\nu d\Omega} \; P_{\nu_\mu \to \nu_e}(E_\nu, \theta) \right) + (\nu \to \bar{\nu}) \,, \tag{5}$$

where n_T is the number density of targets, V is the volume of the detector, θ is the zenith angle direction of the neutrino and t is the observation time. The detector is a cylinder of 250 m diameter and 350 m height, i.e. the total physical mass is of around 15 Mton. The low energy events however are mostly single-string events and we consider the effective volume in this case to be six cylinders of 40 m radius centered around the six densely instrumented ICDC strings.

The second term of Eq. (5), which contains the contribution from oscillations of $\nu_\mu \to \nu_e$, is negligible in practice. This contribution is very small even for the maximum current allowed value of $\sin^2 2\theta_{13}$ and after considering enhancements in the oscillation probabilities due to matter effects inside the Earth. It could, however, become relevant in the presence of non-standard neutrino interactions.

For charged current electron neutrino interactions, the entire energy of the incident neutrinos is transferred to the cascade and thus measured.

For neutral current interactions, only a fraction y of the initial neutrino interaction is transferred to the cascade. Due to the steep energy dependence of the atmospheric neutrino fluxes, their contribution is thus expected to be smaller. The spectrum for neutral current (NC) interactions as a function of the observable energy is given by:

$$\frac{\mathrm{d}N_{NC}}{\mathrm{d}E_{obs}} = 2\pi n_T t \int d\cos\theta\; V \int_{E_{obs}}^{\infty} dE_\nu \frac{d\phi_{\nu_i}}{dE_\nu d\Omega} \frac{1}{E_\nu} P_{\nu_i \to \nu_j}(E_\nu, \theta) \frac{\mathrm{d}\sigma_j^{\mathrm{NC}}}{\mathrm{d}y}(y, E_\nu)\Big|_{y=E_{obs}/E_\nu} + (\nu \to \bar{\nu})\,. \tag{6}$$

For tau neutrinos, charged current (CC) interactions lead to two types of contributions to cascade events: electromagnetic and hadronic, depending on the tau decay mode. The rate for hadronic events is given by:

$$\frac{\mathrm{d}N_\tau^{\mathrm{had}}}{\mathrm{d}E_{obs}} = 2\pi n_T t \int d\cos\theta\; V \int_{E_{obs}}^{\infty} dE_\nu \int_{E_{obs}}^{E_\nu} dE_\tau \frac{d\phi_{\nu_\mu}}{dE_\nu d\Omega} P_{\nu_\mu} \qquad \bar{\nu})\,. \tag{7}$$

For our numerical calculations, we use differential neutrino cross-sections as given by [14] with CTEQ6 parton distribution functions. In terms of dimensionless variables typically used for these cross-sections we have: $\mathrm{d}\sigma_\tau^{\mathrm{CC}}/\mathrm{d}E_\tau \sim 1/E_\nu\, \mathrm{d}\sigma_\tau^{\mathrm{CC}}/\mathrm{d}y$ with $y = 1 - E_\tau/E_\nu$ and $\mathrm{d}n^{\mathrm{had}}/\mathrm{d}E_\tau \sim E_{ons}^2/E_\tau\, \mathrm{d}n^{\mathrm{had}}/\mathrm{d}z$ with $z = 1 - E_{obs}/E_\tau$. It is important to note that for tau neutrinos, tau threshold suppression is still important in the lower energy range discussed here. We have included the threshold corrections following Ref. [15]. The 3.5 GeV tau lepton production threshold energy has made the tau neutrino detection very difficult up to now, since the atmospheric neutrino flux for energies above tau lepton production threshold is very low for existing detectors. For instance, for the SK experiment, and assuming maximal mixing in the $\nu_\mu - \nu_\tau$ sector, only one CC tau neutrino event is expected per kton-year of exposure. The ICDC experiment, which benefits from a much larger instrumented volumen than the SK experiment, is in an unique position to detect tau neutrino interactions, as it has good sensitivity in an energy range where neutrino oscillations lead to a large number of tau neutrinos and, at the same time, is high enough to no longer be strongly affected by tau threshold suppression.

The rate for electromagnetic cascade events is given by an expression similar to Eq. (7), the only difference being in the decay rate $\mathrm{d}n/\mathrm{d}E_\tau$.

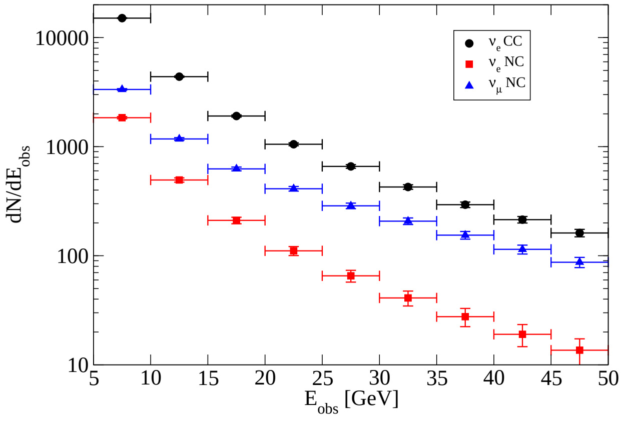

FIG. 2: Electron CC and all flavors NC events for one year ICDC exposure, see text for details in the calculation.

III. RESULTS

Figure 2 shows the cascade rates coming from ν_e charged current interactions and neutral current interactions of ν_e and ν_μ. These events are indistinguishable from the ν_τ cascade events that are of interest to us, so they constitute an irreducible background for the ν_τ search. Figure 3 illustrates the cascade rates from charged current ν_τ interactions followed by hadronic or electromagnetic tau decays, as well as ν_τ neutral current interactions.

While the background is significant, the number of

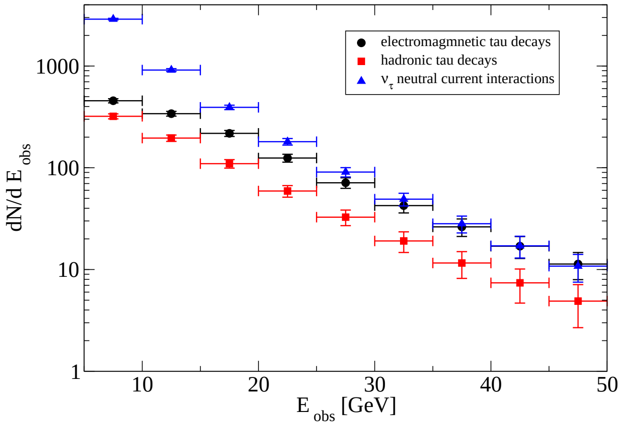

FIG. 3: Tau cascade events for one year of ICDC exposure.

events is very high. Neglecting systematics errors, the statistical significance could be defined as

$$S = \frac{n_s}{\sqrt{n_s + n_b}} \ , \tag{8}$$

n_s being the number of ν_τ events and n_b the number of background events (from ν_e changed current interactions and $\nu_{e,\mu}$ neutral current interactions). A statistically significant (3σ) ν_τ appearance signal could be obtained in only a *few months* of observation. However, systematic uncertainties will limit the analysis. One of the biggest uncertainties is the energy threshold for cascade identification. At the lowest energies considered here, muon track events would be very short [20] and therefore, cascade events and muon track events would be indistinguishable. If cascade events can not be distinguished from muon tracks, the background to the ν_τ signal becomes significantly higher (by about an order of magnitude) due to the contribution from the muon event tracks. Even in the case where muon track events and cascade events can not be distinguished at low energies, the ν_τ signal can become statistically significant in a year of exposure. Good muon track reconstruction would be extremely useful for reducing this systematic uncertainty and might be achievable with the planned additional strings in the center of the detector. There are other systematic uncertainties affecting the analysis, as the knowledge of the interaction cross-sections, atmospheric neutrino fluxes, and other neutrino oscillation parameters. However, these systematic errors are expected to be under control in the next few years, exploiting data from future reactor and accelerator experiments as well as atmospheric neutrino data from the ICDC experiment in different angular and energy ranges than the ones used for the ν_τ analysis. Appearance of tau neutrinos from oscillations of atmospheric ν_μ is thus likely to be detected in the near future.

IV. OUTLOOK

The IceCube detector and its Deep Core array provide a great opportunity for studies of atmospheric neutrinos. Being the largest existing neutrino detector, it will accumulate a huge number of atmospheric neutrino events over an enormous energy range, thus allowing for detailed studies of oscillation physics, Earth density, atmospheric neutrino fluxes and new physics [16]. In order to extract all this information it is necessary to use energy and angular distribution information, as well as flavor composition, all possible to obtain with the IceCube detector. Qualitatively, there are three main energy intervals and three main angular regions which are sensitive to different types of physics.

At very high energies, above 10 TeV, neutrino interaction cross-sections become high enough that neutrinos going through the Earth start getting attenuated [17]. This effect is sensitive to neutrino interaction cross-sections and to the density profile of the Earth.

The "intermediate" energy region, between 50 GeV and 1 TeV can provide good information about the atmospheric neutrino flux, which can be used to improve the uncertainties in the simulated atmospheric neutrino fluxes [18].

In our paper we concentrated on the "low" energy region, below about 40 GeV, where neutrino oscillation effects can be significant. Although the IceCube detector has higher energy thresholds, its low energy extension, the Ice Cube Deep Core array (ICDC), extends the IceCube neutrino detection capabilities in the low energy domain, down to muon or cascade energies as low as 5 GeV. We have shown that tau neutrinos from oscillations of atmospheric muon neutrinos could be detected in the next few years with a high significance level, providing therefore the first sizable sample of tau neutrinos. This large number of tau neutrinos could allow for measurements of ν_τ interaction cross-sections and studies of non-standard neutrino interactions, which are largely unconstrained in the tau sector. In summary, ICDC offers a unique window towards a better understanding of neutrino properties due to its very high atmospheric neutrino statistics. Careful studies of the expected atmospheric neutrino oscillation signals in ICDC, as the one carried out here for the ν_τ appearance signal, are mandatory, since atmospheric neutrinos constitute an irreducible background to astrophysical neutrino searches.

Acknowledgments

This work was supported in part by the NSF grant PHY-0855529. I. M. would like to thank the Aspen Center for Physics where part of this work was completed. O. M. work is supported by the MICINN (Spain) Ramón y Cajal contract, AYA2008-03531 and CSD2007-00060.

[1] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rept. **460**, 1 (2008).

[2] Y. Ashie *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D **71** (2005) 112005.

[3] For a recent overview, see:
IceCube Collaboration, arXiv:0711.0353 [astro-ph]; and
T. A. Collaboration, arXiv:1002.0701 [astro-ph.HE].

[4] O. Schulz [IceCube Collaboration], AIP Conf. Proc. **1085**, 783 (2009); C. Wiebusch and f. t. I. Collaboration, arXiv:0907.2263 [astro-ph.IM].

[5] O. Mena, I. Mocioiu and S. Razzaque, Phys. Rev. D **78**, 093003 (2008) [arXiv:0803.3044 [hep-ph]].

[6] K. Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **97**, 171801 (2006).

[7] M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, arXiv:1001.4524 [hep-ph].

[8] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **103** (2009) 261802.

[9] F. Ardellier *et al.* [Double Chooz Collaboration], arXiv:hep-ex/0606025.

[10] J. K. Ahn [RENO Collaboration], arXiv:1003.1391 [hep-ex].

[11] X. Guo *et al.* [Daya-Bay Collaboration], arXiv:hep-ex/0701029.

[12] M. C. Gonzalez-Garcia and M. Maltoni, Phys. Lett. B **663**, 405 (2008) [arXiv:0802.3699 [hep-ph]].

[13] M. D'Agostino, arXiv:0910.2555 [astro-ph.HE] and arXiv:0910.0215 [astro-ph.HE].

[14] R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. **5**, 81 (1996); R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Phys. Rev. D **58**, 093009 (1998).

[15] S. Kretzer and M. H. Reno, Phys. Rev. D **66**, 113007 (2002). [arXiv:hep-ph/0208187].

[16] M. C. Gonzalez-Garcia, F. Halzen and M. Maltoni, Phys. Rev. D **71**, 093010 (2005) [arXiv:hep-ph/0502223].

[17] M. C. Gonzalez-Garcia, F. Halzen, M. Maltoni and H. K. M. Tanaka, Phys. Rev. Lett. **100**, 061802 (2008).

[18] M. C. Gonzalez-Garcia, M. Maltoni and J. Rojo, JHEP **0610**, 075 (2006).

[19] We have integrated over the zenith angle direction θ of the incident neutrinos, from $c_\nu = -1$ (vertically upward going) up to $c_\nu = 0$ (horizontally incident), being c_ν the cosine of θ.

[20] A 5 GeV muon will have a track in ice of ~ 25 m.