Atmospheric and galactic tau neutrinos

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In memoriam of Akbar Husain

Neutrinos with energy greater than GeV are copiously produced in the \( p(A, p) \) interactions occurring in the earth atmosphere and in our galactic plane. A comparison of the tau and mu neutrino flux in the presence of neutrino oscillations from these two astrophysical sites is presented. It is pointed out that the galactic plane tau neutrino flux dominates over the downward going atmospheric tau neutrino flux at much lower energy value than that for the dominance of the mu neutrino flux from these two sites. Future prospects for possible observations of galactic tau neutrino flux are also briefly mentioned.

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1. Introduction

A present day main motivation for the extra-terrestrial neutrino astronomy is to obtain first evidence of tau neutrinos from the cosmos around us above the relatively well known atmospheric neutrino background. The tau neutrinos are an unavoidable consequence of neutrino flavor mixing as suggested by the high statistics Super-Kamiokande detector (SKK). A recent SKK analysis of the atmospheric neutrino data imply the following range of neutrino mixing parameters

\[
\delta m^2 = (1.3 - 3.0) \cdot 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta > 0.9.
\]  

This is a 90\% C.L. range with the best fit values approximately given by \( \delta m^2 = 2 \cdot 10^{-3} \text{ eV}^2 \) and \( \sin^2 2\theta = 1 \) respectively. This range of neutrino mixing parameters results in purely two flavor oscillation explanation of the zenith angle dependence of the atmospheric mu neutrino deficit, along with another indication. The tau neutrinos as a result of these \( \nu_\mu \rightarrow \nu_\tau \) oscillations are so far however identified on

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On the other hand, the total number of observed non tau neutrinos are by now greater than $10^4$ from various detectors ranging in energy between $10^{-1}$ GeV to $10^3$ GeV. Thus, it is of some interest to estimate the tau neutrino flux from the earth atmosphere as well as from the nearby astrophysical sites such as our galactic plane to provide a more complete basis for the hypothesis of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

The neutrino oscillation probability in the two neutrino flavor approximation is

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left( \frac{l}{l_{osc}} \right).$$

(2)

Here $l$ can be estimated using

$$l = \sqrt{(R_\oplus + h)^2 - R_\oplus^2 \sin^2 \phi - R_\oplus \cos \phi}.$$

(3)

The $l$ is the distance between the detector and the height at which the atmospheric mu neutrinos are produced. The $R_\oplus \simeq 6.4 \cdot 10^3$ km is the earth radius, and $h = 15$ km is the mean altitude at which the atmospheric mu neutrinos are produced. In general, $h$ is not only a function of the zenith angle $\phi$, the neutrino flavor but also the neutrino energy. Also

$$\frac{1}{l_{osc}} = \frac{1.27}{\text{km}} \left( \frac{\text{GeV}}{E} \right) \left( \frac{\delta m^2}{\text{eV}^2} \right),$$

in usual notation.

This paper is organized as follows. In section 2, the mu and tau neutrino flux originating from the earth atmosphere and the galactic plane is briefly discussed. In section 3, the neutrino oscillation effects are studied for both. In section 4, the limited future prospects for possible observations of galactic tau neutrinos are mentioned, whereas in section 4, conclusions are presented.

2. Atmospheric and galactic neutrino flux

Briefly, the incoming cosmic rays interact with the air nuclei $A$, in the earth atmosphere and give rise to mu neutrino flux. For $1 \leq E/\text{GeV} \leq 10^3$, the $\pi^\pm$, $K$ production and their direct and indirect decays are the main sources of mu neutrinos, both being in region of conventional mu neutrino production. The absolute normalization of the conventional atmospheric neutrino flux is presently known to be no better than $(20-25)\%$.

For present estimates, the mu neutrino flux is taken from Ref. [3]. These are neutrino flux calculations in one dimension without geomagnetic field effects. The up down mu neutrino flux is taken to be the same, as the present discussion is independent of any specific detector. At higher energy, the prompt mu neutrino production from $D$’s dominates over the conventional one.

The atmospheric tau neutrino flux arises mainly from $D^\pm_S$ and is calculated in Ref. [10] [11]. The Quark Gluon String Model (QGSM) is used in Ref. [11] to
model the $pA$ interactions. The low energy atmospheric tau neutrino flux is essentially isotropic.\textsuperscript{10} For $E \leq 10^3$ GeV, the atmospheric tau neutrino flux is obtained by re scaling w.r.t new cosmic ray flux spectrum, taking it to be dominantly the protons.\textsuperscript{12,13}

The galactic mu neutrino flux for $E \geq 10^2$ GeV is calculated in Ref.\textsuperscript{14} whereas the galactic plane tau neutrino flux is calculated in Ref.\textsuperscript{11} These calculations consider $pp$ interactions inside the galaxy with target proton number density $\sim 1/cm^3$ along the galactic plane. The tau neutrino production is rather suppressed in the galactic plane relative to mu neutrino production.

The galactic plane mu and tau neutrino flux for $E \leq 10^3$ GeV is obtained by re scaling w.r.t new cosmic ray flux spectrum. The distance inside the galactic plane is taken to be $\sim 10$ kpc where $1$ pc $\simeq 3 \cdot 10^{13}$ km.

The mu neutrino flux is larger than the tau neutrino flux for $E \leq 10^3$ GeV from the two sites. A detailed study that explicitly estimates the tau neutrino flux from the two sites for low energy indicates that the simple re scaling adopted here is a good approximation for $E \geq 10$ GeV.\textsuperscript{15}

3. Effects of neutrino oscillations

In the two flavor approximation, the total tau neutrino flux is

$$\frac{dN_{\nu_{\tau}}}{d(\log_{10}E)} = P(\nu_{\mu} \rightarrow \nu_{\tau}) \cdot \frac{dN_{\nu_{\mu}}}{d(\log_{10}E)} + P(\nu_{\mu} \rightarrow \nu_{\mu}) \cdot \frac{dN_{\nu_{\mu}}}{d(\log_{10}E)}$$ (5)
where \( P(\nu_\mu \rightarrow \nu_\tau) \) is given by Eq. (2) and \( P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau) \). The \( dN/\log E \) is in units of cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\) and is taken according to discussion in section 2.

Three general directions in the earth atmosphere are considered as representative examples to compare the atmospheric tau neutrino flux with the galactic one in the presence of neutrino oscillations. These are downward, horizontal and upward. Fig. 1 depicts the \( l_{osc} \) given by Eq. (4) for the range of \( \delta m^2 \) given by Eq. (1) with maximal mixing. The three distances are taken from Eq. (3), with, for instance, the downward distance is obtained by setting \( \phi = 0 \). The horizontal distance is obtained by setting \( \phi = \pi/2 \).

Using Eq. (5), the total downward going atmospheric tau neutrino flux is estimated. It is then compared with the total galactic plane tau neutrino flux in Fig. 2 for the whole range of \( \delta m^2 \) with maximal mixing. The distance \( l \) for galactic plane neutrinos is taken as \( \sim 5 \) kpc. Since \( l_{osc} < l \), the galactic plane mu neutrinos oscillate before reaching the earth. Also, note that this flux is averaged out for the whole range of \( \delta m^2 \) in the entire considered energy range. The effect of different \( \delta m^2 \) values diminishes for \( E \geq 50 \) GeV for total atmospheric tau neutrino flux. From the figure, it can be seen that the galactic plane tau neutrino flux starts dominating over the downward going atmospheric tau neutrino flux even for \( E \) as low as 10 GeV in the presence of neutrino oscillations. This is a very specific feature of tau neutrinos, and is absent for mu neutrinos. This specific behavior has to do with the neutrino oscillations. The galactic plane tau neutrino flux for \( 1 \leq E/\text{GeV} \leq 10^3 \) in the
The presence of neutrino oscillations can be parameterized as

\[
\frac{dN_{\nu_{\tau}}}{d(\log_{10}E)} = 1.31 \cdot 10^{-5} \cdot \frac{E^{1.07}}{[E + 2.15 \exp(-0.21\sqrt{E})]^{2.74}},
\]

(6)

where \(dN_{\nu_{\tau}}/d(\log_{10}E)\) is in units of \(cm^{-2}\cdot s^{-1}\cdot sr^{-1}\) and on r.h.s. \(E\) is in units of GeV.

In Fig. 3 the galactic plane tau neutrino flux is compared with the atmospheric tau neutrino flux, using Eq. (5) for the three general directions for the atmospheric tau neutrino flux reaching the detector. Here the best fit values of the neutrino mixing parameters are used. The oscillatory nature of the upward going tau neutrino flux can be seen from Eq. (5). The cross over for the galactic tau neutrinos relative to the horizontal atmospheric tau neutrinos occurs at \(\sim 50\) GeV, whereas the same occurs for the upward direction at \(\sim 400\) GeV. The total atmospheric tau neutrino flux is maximum in the upward direction (see Fig. 3). It is minimum in downward direction, relative to the galactic plane tau neutrino flux in the presence of neutrino oscillations, owing to the behavior of \(l/l_{\text{osc}}\) ratio as a function of neutrino energy. Fig. 3 indicates that zenith angle dependence of the total tau neutrino flux can at least in principle help to distinguish between atmospheric and non atmospheric tau neutrino flux. The galactic tau neutrino flux transverse to the galactic plane is three to four orders of magnitude smaller than the galactic plane one.

Fig. 4 gives a comparison of the downward going atmospheric and the galactic plane mu neutrino flux in the presence of neutrino oscillations. For this comparison,
mu neutrino flux is taken from Ref. [16] without rescaling for $E \leq 10^3$ GeV. This mu neutrino flux includes contribution from the $D$'s for $E \geq 6.3 \cdot 10^5$ GeV. The total mu neutrino flux is estimated according to Eq. (5) with appropriate modifications for the best fit values of the two neutrino mixing parameters. In contrast to the possibility of seeing the galactic plane with multi GeV tau neutrinos, note here that with mu neutrinos, it can occur only for $E \geq 10^5$ GeV.

A relevant remark is that for the best fit values of the neutrino mixing parameters, the $P(\nu_\mu \rightarrow \nu_\tau)$ is relatively large along the horizontal and upward directions in the earth atmosphere [see Eq. (2) and Fig. 1] for $1 \leq E/GeV \leq 10$. So essentially the atmospheric mu neutrino flux in the absence of neutrino oscillations alone determines the total atmospheric tau neutrino flux in comparison with the total galactic tau neutrino flux.

4. Prospects for possible observations
For $10 \leq E/GeV \leq 10^3$, a signature for the tau neutrinos is to measure the energy spectrum of the tau lepton induced electromagnetic and hadronic showers produced in tau neutrino nucleon interactions occurring inside a densely instrumented Cherenkov radiation detector [17]. Though, it is a challenging task to distinguish between tau and non tau neutrinos for the present generation of detectors in the above energy range [18], however certain shower signatures remain distinctive for tau neutrinos [17].

The galactic tau neutrino induced shower production rate can be approximately
estimated by convolving the total galactic tau neutrino flux in the presence of neutrino oscillations, given by Eq. (6) with the $\sigma_{\nu_\tau N}^{\text{tot}}$, where $\sigma_{\nu_\tau N}^{\text{tot}} = \sigma_{\nu_\tau N}^{CC} + \sigma_{\nu_\tau N}^{NC}$ for $10 \leq E/\text{GeV} \leq 10^3$. For recent evaluations of $\sigma_{\nu_\tau N}^{\text{tot}}$, see Ref. [19]. The possible tau lepton polarization effects [20] are not taken into account in the event rate estimates presented here.

Table 1. Galactic tau neutrino induced shower event rate. Details are given in the text.

| Energy Bin (GeV) | $N_{\nu_\tau} (\text{Mt} \cdot \text{yr} \cdot 2\pi \text{sr})^{-1}$ |
|-----------------|--------------------------------------------------|
| 10 – 31.62      | 0.52                                            |
| 31.62 – 100     | 0.50                                            |
| 100 – 316.2     | 0.30                                            |
| 316.2 – 1000    | 0.17                                            |

Table 1 gives the galactic tau neutrino induced shower event rate for a 1 Mega ton detector, in units of $(\text{Mt} \cdot \text{yr})^{-1}$ in $2\pi$ steradians of upper hemisphere in four wide logarithmically equally spaced energy bins. The table indicates that with a 3 to 5 year data collection time for a one Mega ton detector, the galactic tau neutrino induced shower event rate can be in the range of $(1 – 10)$ for $E \geq 10$ GeV. This detector faces only the downward going atmospheric tau neutrino flux as background to the dominant galactic plane tau neutrino flux in the presence of neutrino oscillations.

5. Conclusions

1. The effects of neutrino oscillations on low energy ($E \leq 10^3$ GeV) tau neutrino flux produced in the earth atmosphere and in our galactic plane are presented in two neutrino flavor approximation.

2. The galactic plane should be observable with tau neutrinos with energy $\geq$ 10 GeV, depending on the orientation of the concerned detector w.r.t. galactic center/plane at the time of observation. The observation of galactic plane with multi GeV tau neutrinos is in sharp contrast to the case of mu neutrinos with which the galactic plane is observable only with energy $\geq$ 10$^5$ GeV for the same orientation of the detector.

3. This observation may also have some relevance for the long baseline experiments searching for the tau neutrinos in $\nu_\mu \rightarrow \nu_\tau$ oscillations [21].

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