High Energy Astrophysical Tau Neutrinos: The Expectations

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Aspects related to production, propagation and prospects for observations of high energy astrophysical tau neutrinos originating from some representative extra terrestrial sources such as atmosphere of earth, our galactic plane as well as possibly from distant sites of gamma ray bursts in the energy range $10^3 \leq E/\text{GeV} \leq 10^{11}$ are reviewed.

1. INTRODUCTION

A search for high energy astrophysical tau neutrinos will not only yield quite useful information about some of the highest energy phenomenons occurring in the present universe related to the origin of observed high energy gamma rays and ultra high energy cosmic rays but also can possibly probe physics beyond standard model of particle physics.

The representative extra terrestrial sources of high energy astrophysical tau neutrinos with energy greater than $10^3$ GeV include the atmosphere of earth, the plane of our galaxy, the center of distant (active) galaxies as well as possibly the sites of gamma ray bursts (GRBs). Here, I summarize the present status of intrinsic flux estimates for high energy astrophysical tau neutrinos, both originating from the source itself as well as during propagation (of ultra high energy cosmic rays, assumed to be dominantly protons here). In light of recently growing empirical evidence for neutrino flavor oscillations, I will mention the effects of neutrino flavor mixing on this intrinsic flux (in two flavor approximation, for simplicity). The presently envisaged prospects for possible observations of intrinsic and oscillated high energy astrophysical tau neutrino flux through several different detection strategies will also be presented. For a recent brief review on high energy astrophysical neutrinos, see [1].

2. HIGH ENERGY ASTROPHYSICAL TAU NEUTRINOS

2.1. Production

High energy astrophysical tau neutrino production can occur in $pp$ and $p\gamma$ interactions taking place in cosmos. These interactions produce unstable hadrons such as $D_S$ and $B_S$. At further higher center of mass energy, production of other heavier states such as $tt$, $W^\ast$ as well as $Z^\ast$ is also possible. All of these states decay into $\nu_\tau$ directly or indirectly, with $D_S$ being the lightest one to decay directly into $\nu_\tau$. Copious production of $\pi^\pm$ also occurs in these interactions, which decay into non tau neutrinos. The absolute normalization of high energy astrophysical tau neutrinos is fixed in a similar way as for high energy astrophysical muon neutrinos. In general, the $D_S$ dominates the tau neutrino production over the entire energy range under consideration here. In these interactions, the target protons and photons are considered to be present inside the source as well as in the interstellar medium between the source and the detector. The high energy tau neutrinos possibly originating from GRBs are an example of the former situation, whereas the galactic plane and GZK tau neutrinos are examples for the latter situation. The GZK tau neutrinos are a result of neutrino flavor oscillations of GZK muon neutrinos, which are produced in $p\gamma \rightarrow \Delta \rightarrow \pi^\pm X$ interactions [2]. The atmospheric tau neutrino flux is estimated in [3], whereas the galactic tau neutrino flux is estimated and compared with atmospheric one in [4]. In these estimates, the tau...
neutrino flux is obtained by solving the system of coupled cascade equations that describes the propagation of protons, unstable hadrons and leptons in the presence of a varying target density medium.

Depending upon the distance to the source and the concerned energy range, the production of high energy tau neutrinos may or may not become comparable to the high energy muon neutrinos. For instance, in case of galactic plane, it is the intrinsic muon neutrino flux that dominates, however, it is not the case for atmosphere of earth for the whole energy range under consideration here. In the atmosphere of earth, for \( E > 10^5 \) GeV, intrinsic tau neutrino production is quite comparable to intrinsic muon neutrino production as both originate from \( D \)'s.

2.2. Oscillations during propagation

The empirical evidence for neutrino flavor mixing is now rather compelling. In particular, the explanation of recent statistically significant data concerning the atmospheric muon neutrino deficit is suggestive of \( \nu_\mu \rightarrow \nu_\tau \) flavor oscillations. In the context of two neutrino flavors, the oscillation probability formula is

\[
P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \cdot \sin^2(l/l_{\text{osc}}).
\]

Equation 1 ignores the effect of a possible enhancement in \( \theta \) due to (coherent forward) neutrino scattering during propagation. This approximation is presently justified, given the current status of high energy astrophysical tau neutrino observations. Further discussion on propagation effects of mixed high energy (tau) neutrinos can be found in [10], whereas for unmixed high energy tau neutrinos propagation effects (mainly related to observations), see [11].

Here \( \theta \) is neutrino flavor mixing angle between \( \nu_\mu \) and \( \nu_\tau \), whereas \( l_{\text{osc}} \equiv \pi E/\delta m^2 \). Presently, the global best fit values of \( \sin^2 2\theta \) and \( \delta m^2 \) are essentially \( \sim 1 \) and \( \sim 2.5 \cdot 10^{-3} \) eV\(^2\), respectively [6]. In Eq. (1), \( l \) is the distance between the source and the detector. In case of complete averaging, namely when \( l \gg l_{\text{osc}} \), the second \( \sin^2 \) factor is equal to 0.5. Taking \( \sin^2 2\theta \sim 1 \), I obtain, \( P \leq 0.5 \). This is substantial, as compared to the intrinsic production probability of high energy astrophysical tau neutrinos, which is rather suppressed relative to that for muon neutrinos in some distant astrophysical sites as mentioned in the last section. High energy astrophysical tau neutrinos thus seem to be roughly as abundant as high energy muon neutrinos except from the atmosphere of earth, given the present status of neutrino flavor mixing. For a description of three (and four) neutrino flavor mixing effects for high energy astrophysical tau neutrinos, see [4].

Figure 1. Galactic plane, horizontal atmospheric and GZK high energy tau neutrino flux under the assumption of (two) neutrino flavor mixing. For comparison, tau neutrino flux in a fireball model of GRB is also shown [7]. The energy range shown covers all the presently envisaged high energy (tau) neutrino detectors.
sentative extra terrestrial sources.

Let me emphasize here a simple point that neutrino flavor mixing is an intrinsic property of the neutrino state. It has nothing to do with the energy of the neutrino. It is the probability of neutrino oscillation that depends on neutrino energy.

2.3. Prospects for possible observations

Present status of currently operating and under planning high energy (tau) neutrino detectors is described in [11]. In general, the high energy astrophysical tau neutrino flux arrives at an earth based detector in three general directions.

2.3.1. Downward going

It might be possible to search for downward going high energy tau neutrinos through double shower technique [12]. Quantitative details of this suggestion for a typical Km$^3$ instrumented volume (ice) Cherenkov radiation detector were given in [13]. The event simulations done by IceCube collaboration based on [13] can be found in [14]. In principle, this technique may also be feasibly implemented in other alternative detection methods as well. A high energy tau neutrino flux at the level of $\sim 10^{-11}\text{cm}^2\text{s}^{-1}\text{sr}^{-1}$ gives several double shower type events per year irrespective of its origin in an instrumented volume of Km$^3$ for an incident energy of several $10^6$ GeV.

For the energy range between $10^3$ GeV to $5 \cdot 10^5$ GeV, the two showers will be quite difficult to separate from each other for typical Cherenkov radiation detectors. Between $5 \cdot 10^5$ GeV and $10^6$ GeV, the proposed Megaton detectors are a possibility, whereas between $2 \cdot 10^7$ GeV and $5 \cdot 10^8$ GeV, detectors with instrumented volume of more than Km$^3$ may be needed. On the other hand for energy greater than $10^9$ GeV, the two showers are too distant from each other (essentially hundreds of Km), so are difficult to track for presently planned (single) earth based detectors [15].

2.3.2. Quasi horizontal

The possibility of observation of near horizontal high energy tau neutrinos through double shower technique for Pierre Auger array was briefly considered in [16]. Following [13], an approximately half an order of magnitude energy interval, namely $5 \cdot 10^8 \leq E/\text{GeV} \leq 10^9$, was obtained by requiring that the longitudinal profile of the two showers do not overlap in the array length, taken to be $\sim 60$ Km (see Fig. 2 and Fig. 3 for illustration). The two showers are considered to develop in the air. For energy above $10^9$ GeV, the decay length of the tau lepton in air is larger than the size of the array and the double shower signature can not be observed. However, the energy at which the two showers start separating in Pierre Auger array lies below the presently planned threshold for high energy neutrino detection. The crucial factor here being the difference in the incident tau neutrino energy dependence on the spread and separation of the two showers. The double shower type event rate for Pierre Auger array can be estimated following [13].

2.3.3. Upward going

The upward going tau neutrino flux is suppressed by the deep inelastic tau neutrino nucleon scattering inside the earth for $E \geq 5 \cdot 10^4$ GeV [17]. In fact, for upward going high energy tau neutrinos which cross almost all the diameter of the earth, the suppression in the incident flux is essentially exponential.

A variant of the last two situations is a scenario in which the high energy tau neutrino nucleon

Figure 2. Comparison of the tau lepton decay length and the shower length of the first shower (defined as twice the depth at maximum) in air.
charged current deep inelastic interaction occurs just once inside the earth and a tau lepton is produced. This tau lepton after exiting the earth produces an air shower which might possibly be measured in a future large earth, plane, balloon or space based detector [18].

3. CONCLUSIONS

- So far, there are only few explicit estimates for intrinsic high energy astrophysical tau neutrino flux. Existing ones are for atmosphere of earth and for our galaxy. 
- Neutrino flavor oscillations is an interesting possibility to expect $\nu_\tau$ from $\nu_\mu$. For distant astrophysical tau neutrino sources in the energy range $10^3 \leq E / \text{GeV} \leq 10^{11}$, presently $dN_{\nu_\tau}^\text{tot}/d(\log_{10}E) \leq 0.5 \cdot dN_{\nu_\mu}^\text{int}/d(\log_{10}E)$.
- High energy astrophysical tau neutrino observation can possibly be achieved in future large arrays through several different detection strategies.

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