Neutrino Conversions in Active Galactic Nuclei

Athar Husain

Department of Physics, Tokyo Metropolitan University,
Minami-Osawa 1-1, Hachioji-Shi, Tokyo 192-0397, Japan

Abstract

I discuss the possibility of production of high energy cosmic neutrinos \( (E \geq 10^6 \text{ GeV}) \) in cores of active galactic nuclei and study some of the effects of neutrino mixing on their subsequent propagation. I also discuss the prospects for observations of these high energy cosmic neutrinos in new km\(^2\) surface area underwater/ice neutrino telescopes.

1 Introduction

In this contribution I discuss the possibility of production of high energy cosmic neutrinos \( (E \geq 10^6 \text{ GeV}) \) in cores of Active Galactic Nuclei (AGN) originating from proton acceleration, the effects of three flavour neutrino mixing on these high energy cosmic neutrino fluxes and the prospects for their observations in new km\(^2\) surface area underwater/ice neutrino telescopes.

In addition to AGNs, high energy cosmic neutrinos may also be produced in several currently envisaged other cosmologically distant astrophysical sources. These sources may include, for instance, Gamma Ray Burst fireballs and Topological Defects [1]. For some possible effects of neutrino mixing other than the flavour one on high energy cosmic neutrino fluxes, see [2]. The present study is particularly useful as several high energy neutrino telescopes are now at their rather advanced stage of development and deployment [3].

I start in Section 2 with a brief description of possibility of production of high energy cosmic neutrinos and discuss in some detail the effects of three flavour neutrino mixing on their subsequent propagation and further discuss the prospects for their detection. In Section 3, I summarize the results.
2 High Energy Neutrinos from AGNs

2.1 Production

High energy cosmic neutrinos may mainly be produced either in $p\gamma$ or in $pp$ collisions in a cosmologically distant environment.

In $p\gamma$ collisions, high energy $\nu_e$ and $\nu_\mu$ are mainly produced through $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ (typically with $\nu_e/\nu_\mu \sim 1/2$). The same collisions will give rise to a greatly suppressed high energy $\nu_\tau$ flux ($\nu_\tau/\nu_e,\nu_\mu < 10^{-5}$) mainly through $p + \gamma \rightarrow D_S^+ + \Lambda^0 + \bar{D}_S^0$. In $pp$ collisions, the $\nu_\tau$ flux may be obtained through $p + p \rightarrow D_S^+ + X$. The relatively small cross-section for $D_S^+$ production together with the low branching ratio into $\nu_\tau$ implies that the $\nu_\tau$ flux in $pp$ collisions is also suppressed up to 5 orders of magnitude relative to $\nu_e$ and/or $\nu_\mu$ fluxes (which are mainly produced through $\pi^+$) [4].

2.2 Propagation

Matter effects on vacuum neutrino oscillations are relevant if $G_F \rho/m_N \sim \delta m^2/2E$. Using $\rho$ from Ref. [5] as an example, it turns out that matter effects are absent for $\delta m^2 \geq O(10^{-10})$ eV$^2$. Matter effects are not expected to be important in the neutrino production regions around AGN and will not be further discussed here.

In the framework of three flavour analysis, the flavour precession probability from $\alpha$ to $\beta$ neutrino flavour is [6]

$$P(\nu_\alpha \rightarrow \nu_\beta) \equiv P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

$$+ \sum_{i \neq j} U_{\alpha i} U_{\alpha j}^* U_{\beta j}^* U_{\beta i} \cos \left( \frac{2\pi L}{l_{ij}} \right), \quad (1)$$

where $\alpha, \beta = e, \mu, \text{or } \tau$. $U$ is the $3 \times 3$ MNS mixing matrix and can be obtained in usual notation through

$$U \equiv R_{23}(\theta_1) \text{diag}(e^{-i\delta/2}, 1, e^{i\delta/2})$$

$$\cdot R_{12}(\theta_2) \text{diag}(e^{i\delta/2}, 1, e^{-i\delta/2}) R_{13}(\theta_3), \quad (2)$$

thus coinciding with the standard form given by the Particle Data Group [7]. In Eq. (1), $l_{ij} \simeq 4\pi E/\delta m_{ij}^2$ with $\delta m_{ij}^2 \equiv |m_i^2 - m_j^2|$ and $L$
is the distance between the source and the detector. For simplicity, I assume here a vanishing value for CP violating phase $\delta$ and $\theta_{31}$ in $U$.

At present, the atmospheric muon and solar electron neutrino deficits can be explained with oscillations among three active neutrinos [8]. For this, typically, $\delta m^2 \sim O(10^{-3})$ eV$^2$ and $\sin^2 2\theta \sim O(1)$ for the explanation of atmospheric muon neutrino deficit, whereas for the explanation of solar electron neutrino deficit, we may have $\delta m^2 \sim O(10^{-5})$ eV$^2$ and $\sin^2 2\theta \sim O(1)$ [just so] or $\delta m^2 \sim O(10^{-5})$ eV$^2$ and $\sin^2 2\theta \sim O(1)$ [SMA (MSW)] or $\delta m^2 \sim O(10^{-5})$ eV$^2$ and $\sin^2 2\theta \sim O(1)$ [LMA (MSW)]. The present status of data thus permits multiple oscillation solutions to solar neutrino deficit. I intend to discuss here implications of these mixings for high energy cosmic neutrino propagation.

In the above explanations, the total range of $\delta m^2$ is $10^{-10} \leq \delta m^2 / \text{eV}^2 \leq 10^{-3}$ irrespective of neutrino flavour. The typical energy span relevant for possible flavour identification for high energy cosmic neutrinos is $2 \cdot 10^6 \leq E / \text{GeV} \leq 2 \cdot 10^7$ in which currently the neutrino flux from cores of AGNs dominate. Taking a typical distance between the AGN and our galaxy as $L \sim 100$ Mpc (where 1 pc $\sim 3 \cdot 10^{16}$ m), note that cos term in Eq. (1) vanishes and so Eq. (1) reduces to

$$\langle P_{\alpha \beta} \rangle \simeq \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2.$$  

(3)

It is assumed here that no relatively dense objects exist between the AGN and the earth so as to effect significantly this oscillations pattern. Note also that since $\langle P_{\alpha \beta} \rangle$ in above Eq. is symmetric under the exchange of indices $\alpha$ and $\beta$ implying that no $T$ (or $CP$) violation effects arise in neutrino vacuum flavour oscillations for high energy cosmic neutrinos [9].

Let me denote by $F^0_{\alpha}$, the intrinsic neutrino fluxes. From the discussion in the previous Subsection, it follows that $F^0_{\mu} : F^0_{\tau} : F^0_{e} = 1 : 2 : 0$. In order to estimate the final (downward going) flux ratios of high energy cosmic neutrinos reaching on earth, let me introduce a $3 \times 3$ matrix of vacuum flavour precession probabilities such that

$$F_{\alpha} = \sum_{\beta} \langle P_{\alpha \beta} \rangle F^0_{\beta},$$  

(4)

where the unitarity conditions for $\langle P_{\alpha \beta} \rangle$ read as

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\[ \langle P_{ee} \rangle + \langle P_{e\mu} \rangle + \langle P_{e\tau} \rangle = 1, \]
\[ \langle P_{e\mu} \rangle + \langle P_{\mu\mu} \rangle + \langle P_{\mu\tau} \rangle = 1, \]
\[ \langle P_{e\tau} \rangle + \langle P_{\mu\tau} \rangle + \langle P_{\tau\tau} \rangle = 1. \] (5)

The explicit form for the matrix \( \langle P \rangle \) in case of just so flavour oscillations as solution to solar neutrino problem along with the solution to atmospheric neutrino deficit in terms of \( \nu_\mu \) to \( \nu_\tau \) oscillations with maximal mixing is
\[
\langle P \rangle = \begin{pmatrix}
\frac{1}{2} & 1/4 & 1/4 \\
1/4 & 3/8 & 3/8 \\
1/4 & 3/8 & 3/8
\end{pmatrix}.
\] (6)

Using Eq. (6) and Eq. (4), it follows that \( F_e : F_\mu : F_\tau = 1 : 1 : 1 \) at the level of \( F^0 \). Also, Eq. (5) is satisfied. The same flux ratio is obtained in the remaining two cases for which the corresponding \( \langle P \rangle \) matrices are: [for SMA (MSW)]
\[
\langle P \rangle = \begin{pmatrix}
1 & 0 & 0 \\
0 & 1/2 & 1/2 \\
0 & 1/2 & 1/2
\end{pmatrix},
\] (7)

whereas in case of LMA (MSW),
\[
\langle P \rangle = \begin{pmatrix}
\frac{5}{8} & 3/16 & 3/16 \\
3/16 & 13/32 & 13/32 \\
3/16 & 13/32 & 13/32
\end{pmatrix}.
\] (8)

Thus, essentially independent of the oscillation solutions for solar neutrino problem, it follows that \( F_e : F_\mu : F_\tau = 1 : 1 : 1 \). The deviations from these ratios are estimated to be small [10].

Summarizing, although intrinsically the downward going high energy cosmic tau neutrino flux is negligibly small however because of vacuum flavour oscillations it becomes comparable to \( \nu_e \) flux thus providing some prospects for its possible detection.

### 2.3 Prospects for detection

I briefly mention here the prospects for detection of downward going high energy cosmic tau neutrinos through double shower technique [11]. For prospects of observations of high energy cosmic tau
neutrinos other than double shower technique, see [12], whereas for possibility of detection of non tau neutrinos, see [13].

The downward going tau neutrinos reaching close to the surface of the detector may undergo a charged current deep inelastic scattering with nuclei inside/near the detector and produce a tau lepton in addition to a hadronic shower. This tau lepton traverses a distance, on average proportional to its energy, before it decays back into a tau neutrino and a second shower most often induced by decay hadrons. The second shower is expected to carry about twice as much energy as the first and such double shower signals are commonly referred to as a double bangs. As tau leptons are not expected to have further relevant interactions (with high energy loss) in their decay timescale, the two showers should be separated by a clean $\mu$-like track.

The calculation of downward going contained but separable double shower event rate can be carried out by replacing the muon range expression with the tau range expression and then subtracting it from the linear size of a typical high energy neutrino telescope in the event rate formula while using the expected $\nu_\tau$ flux spectrum given by Eq. (4). This ensures that the two separate showers are contained within km of the underwater/ice detector. Here, I restrict myself by men-
tioning that the expected number of contained but separable double showers induced by downward going high energy tau neutrinos for $E \sim 2 \cdot 10^6 \text{ GeV}$ may be $\sim \mathcal{O}(10)/\text{yr}\cdot\text{sr}$ irrespective of the oscillation solutions of solar neutrino problem, if one uses the $F_0^\nu$ from Ref. [5] as an example. At this energy, the two showers initiated by the downward going high energy cosmic tau neutrinos are well separated ($\geq 70 \text{ m}$) such that the size of the second shower is essentially 2 times the first shower and the two showers are connected by a $\mu$–like track (see Fig. 1). This identification, if empirically realized, may provide a possibility to isolate $\nu_\tau$ flavour from the rest of neutrino flavors. The chance of having double shower events induced by non tau neutrinos is negligibly small for relevant energies.

3 Conclusions

1. Intrinsically, the flux of high energy cosmic tau neutrinos is quite small, relative to non tau flavour neutrinos, typically being $F_0^\nu/ F_0^{\mu,\tau} < 10^{-5}$ (whereas $F_0^{\mu}/F_0^{\tau} \sim 1/2$) from cosmologically distant astrophysical sources, namely, for instance, cores of Active Galactic Nuclei.

2. Because of neutrino oscillations, this ratio can be greatly enhanced. In the context of three flavour neutrino mixing scheme which can accommodate the oscillation solutions to solar and atmospheric neutrino deficits in terms of oscillations between three active neutrinos, the final ratio of fluxes of downward going high energy cosmic neutrinos on earth is $F_\tau \sim F_\mu \sim F_\nu$ essentially irrespective of the oscillation solutions to solar neutrino problem.

3. This enhancement in high energy cosmic tau neutrino flux may lead to the possibility of its detection in $\text{km}^2$ surface area high energy neutrino telescopes. For $2 \cdot 10^6 \leq E/\text{GeV} \leq 2 \cdot 10^7$, the downward going high energy cosmic tau neutrinos may produce a double shower signature because of charged current deep inelastic scattering followed by a subsequent hadronic decay of the associated tau lepton.

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References


