Tau neutrinos from active galactic nuclei

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We study the appearance of $\nu_\tau$ from active galactic nuclei (AGN) through neutrino spin-flip. We consider two situations: i) Spin (flavour)-precession in a reasonable strength of magnetic field in AGN, $B_{AGN}$ ii) Adiabatically resonant conversions caused by an interplay of $B_{AGN}$ and the violation of equivalence principle. Observational consequences for both situations are discussed.

1. INTRODUCTION

Neutrinos are currently understood as elementary particles having spin $1/2$ ($\bar{\nu}_H$). Neutrinos have no colour charge, no electromagnetic charge, however neutrinos have weak charge and consequently neutrinos interact only weakly. Light stable neutrinos come in three flavours, namely, $\nu_e$, $\nu_\mu$ and $\nu_\tau$ alongwith corresponding antiparticles. Exact value of the mass of neutrino is still unknown. All direct and indirect searches so far imply an upper bound on neutrino masses. The nonzero mass of the neutrino, however, on quite general grounds imply nonzero neutrino magnetic moment, $\mu$ [1]. We intend to discuss here a phenomenological implication of $\mu$ in $B_{AGN}$.

Some galaxies have quite bright centers. The luminosity of these galaxies typically reach $10^{44} - 10^{48}$ erg/sec. In general, AGNs refers to these bright centers. It is hypothesized that the existence of a supermassive black hole ($M \sim (10^6 - 10^{10}) M_\odot$) [here $M_\odot$ is solar mass; $M_\odot \sim 2 \cdot 10^{33}$ g] may explain the observed brightness as this supermassive blackhole captures the matter around it through accretion. This supermassive black-hole is hypothesized to be formed by the collapse of a cluster of stars. During and after accretion, accelerated protons may collide with other protons and/or with the ambient photon field present in the vicinity of an AGN or/and in the associated jets (see latter in this Sect.) and produce unstable hadrons. These unstable hadrons decay mainly into neutral and charged pions. The neutral pions decay into photons and thus may explain the observed brightness whereas the charged pions mainly decay into electron and muon neutrinos and corresponding antineutrinos. For an update review of various flux estimates for $\nu_e$ and $\nu_\mu$ from AGNs (as well as from some other interesting astrophysical sources), see [2]. The same protons (hypothesized to be present in the vicinity of an AGN) and photons may give rise to $\nu_\tau$ (and $\bar{\nu}_\tau$) in a small number, through, for instance, $p + \gamma \rightarrow D_S^+ + \Lambda^0 + D^0$. It is so because the production cross for $D_S^+$ is essentially two orders of magnitude lower than, for instance, that of $\Delta^+$ (a main source of $\nu_e$ and $\nu_\mu$) for the relevant center of mass energy scale. The branching ratio of $D_S^+ \rightarrow \nu_\tau$ (and $\bar{\nu}_\tau$) is approximately an order of magnitude lower than for $\Delta^+$ to decay into $\nu_e$ and $\nu_\mu$. These two suppression factors alongwith the relevant kinematic limits give approximately the ratio of fluxes of tau neutrinos and muon (anti) neutrinos as $\nu_\tau/\bar{\nu}_\mu \lesssim 10^{-3}$ [3].

Here, we discuss a possibility to enhance this ratio, that is, to obtain, $\nu_\tau/\bar{\nu}_\mu > 10^{-3}$, through neutrino spin-flip induced by violation of equivalence principle (VEP) [4]. The VEP arises as different flavours of neutrinos may couple differently to gravity [5,6]. This essentially results from the realization that flavour eigenstates of neutrinos may be the admixture of the gravity eigenstates of neutrinos with different gravitational couplings. We study here mainly the spin-flip for Majorana type neutrinos in the vicinity of the cores of active galaxies which we hereafter refer to as AGNs. Some AGNs give off a jet of matter that stream...
out from the nucleus in a transverse plane and produces hot spots when the jet strikes the surrounding matter at its other end. For a discussion of neutrino spin-flip in jets and hot spots, see [8–11]. Previously, the neutrino spin-flip effects for AGN neutrinos due to VEP are studied in [8,10]. The VEP is parameterized by a dimensionless parameter $\Delta f$. In [8], by demanding an adiabatic conversion to occur, a lower bound on $\mu$ was obtained in terms of $\Delta f$. In [8], neutrino spin-flip in AGN due to gravitational effects is studied, whereas in [10], the effect of possible random fluctuation in $B_{AGN}$ on neutrino precession is considered. There is no detailed study of the implications of spin-flip effects for neutrinos with small $\delta m^2$ originating from AGN without gravitational effects and/or VEP. In this context, we address two different aspects of spin-flip for high energy neutrinos, viz, the spin (flavour)-precession with/without VEP in $B_{AGN}$; and the adiabatic/nonadiabatic conversion due to an interplay of $B_{AGN}$ and the VEP. We point out that, for latter type of conversion effect, a $\Delta f$ of the order of $10^{-39} - 10^{-29}$ depending on $\delta m^2$ gives reasonably large conversion probabilities for a suitable choice of parameters of the AGN model.

The present study is particularly welcome as the new ice/underwater Čerenkov light detectors namely AMANDA, Baikal, NESTOR and ANITA will have not only the energy but also the angle and flavour resolutions for high energy neutrinos from AGNs [11]. These characteristics make these neutrino telescopes especially suitable for the study of various high energy neutrino conversions.

The plan of the paper is as follows. In Sect. 2, we briefly discuss the matter density and magnetic field profiles in AGN. In Sect. 3, we discuss the spin (flavour)-precession due to VEP and determine the value of $\Delta f$ needed to have the precession probability greater than 1/2. In the same Sect., we consider in some detail the resonant/nonresonant conversions induced by an interplay of $B_{AGN}$, and the VEP along with corresponding observational consequences and finally in Sect. 4, we summarize our results.

2. THE MATTER DENSITY AND MAGNETIC FIELD IN AGN

Neutrino spin-precession in the context of the Sun was discussed in [3]. It was pointed out that the matter effects tend to suppress the precession effect. As shown below, for AGN, matter effects arising due to coherent forward scattering of neutrinos off the background are negligible (similar estimate for other astrophysical systems like Sun and Collapsing Stars shows that the matter effects are indeed nonnegligible in most part of these systems). The essential conditions needed for appreciable spin-precession are: i) $\mu Br \gtrsim 1$, i.e., $B$ must be large enough in the region $r$; ii) the smallness of the usual matter effects, so that neutrino spin-precession is not suppressed (see below); and iii) there should be no reverse spin-precession of neutrinos on their way to earth. As for the third essential condition on the observed intergalactic magnetic field for the nearby galaxies is estimated to be $\sim O(10^{-9} G)$ at a scale of Mpc. Taking a typical distance between the earth and the AGN as $\sim 100$ Mpc, we note that the effect induced by intergalactic/galactic magnetic field is quite small as the galactic magnetic field is $\sim O(10^{-6} G)$, thus causing negligible reverse spin-precession.

According to [3], the density contrast in the vicinity of AGN has the following profile: $\rho(x) = \rho_0 f(x)$ where $\rho_0 \approx 1.4 \times 10^{-13}$ g/cm$^3$ and $f(x) \approx x^{-2.5}\left(1 - 0.1x^{0.31}\right)^{-1}$ as we take the AGN luminosity to be $10^{46}$ erg/sec with $x \equiv r/R_S$, $R_S$ being the Schwarzchild radius of AGN: $R_S \approx 3 \times 10^{11} \left(\frac{\text{M}_{\odot}}{M_{\odot}}\right)$ m. We take the distance traversed by the neutrinos to be $10 < x < 100$ in the vicinity of AGN. These imply that the width of the matter traversed by neutrinos in the vicinity of the AGN is $l_{AGN} \sim (10^{-2} - 10^{-1})$ g/cm$^2$. In the presence of matter, the effective width of matter needed for appreciable spin-flip, on the other hand, is $l_0 \equiv \sqrt{2\pi m_N G_F^{-1}} \sim 2 \times 10^4$ g/cm$^2 \gg l_{AGN}$, much larger than $l_{AGN}$. Hence, from now on, we ignore the matter effects.

We consider now the magnetic field in the vicinity of AGN with the following profile [3]

$$B_{AGN}(x) = B_0 g(x),$$

where
where \( B_0 \sim 5.5 \times 10^{14} \) G and \( g(x) = x^{-1.75}(1 - 0.17e^{0.31})^{-0.5} \) for \( 10 < x < 100 \). We will use this \( B_{AGN} \) in our estimates.

### 3. NEUTRINO SPIN-FLIP DUE TO VEP

The evolution equation for the two neutrino state for vanishing gravity mixing angle and the vanishing vacuum mixing angle is governed by an effective hamiltonian whose diagonal elements may be written as \([4,5]\)

\[
\begin{align*}
H_\mu &= 0, \\
H_\tau &= \delta - V_G.
\end{align*}
\]  

In Eq. (2), \( \delta = \delta m^2/2E \), where \( \delta m^2 = m^2(\nu_\tau) - m^2(\bar{\nu}_\mu) > 0 \) with \( E \) being the neutrino energy. \( V_G \) is the effective potential felt by the neutrinos at a distance \( r \) from a gravitational source of mass \( M \) due to VEP and is given by \([\Box]\)

\[
V_G \equiv \Delta f \phi(r)E, \quad (3)
\]

where \( \Delta f = (f_3 - f_2)(f_3 + f_2)^{-1} \) and \( \phi(r) = G_N M r^{-1} \) is the gravitational potential in the Keplerian approximation, with \( f_2 G_N \) and \( f_3 G_N \) being respectively the gravitational couplings for \( \bar{\nu}_\mu \) and \( \nu_\tau \), such that \( f_2 \neq f_3 \). The possibility of vanishing gravity and vacuum mixing angles in Eq. (2) allows us to identify the range of \( \Delta f \) relevant for neutrino magnetic moment effects only. We now propose to study in some detail the various possibilities arising from the relative comparison between \( \delta \) and \( V_G \) in Eq. (2).

#### Case 1. \( V_G = 0 \).

For constant \( B \), we obtain the following expression for precession probability \( P(\bar{\nu}_\mu \rightarrow \nu_\tau) \) from Eq. (2):

\[
P(\bar{\nu}_\mu \rightarrow \nu_\tau) = \left( \frac{(2 \mu B)^2}{(2 \mu B)^2 + X^2} \right) \sin^2 \left( \frac{r\sqrt{D}}{2} \right), \quad (4)
\]

with \( X = \delta \) and \( D \) being the denominator in the prefactor of phase . We now discuss the relative comparison between \( 2 \mu B \) and \( \delta \) and evaluate \( P \) for corresponding \( \delta m^2 \) range.

a) \( \delta \ll 2 \mu B \). Using \( B \) given in Eq. (1) for \( \mu \sim 10^{-12} \mu_B \) \([16]\), we obtain \( \delta m^2 \ll 5 \times 10^{-4} \) eV\(^2\) with \( E \sim 1 \) PeV. We take here \( \delta m^2 \sim 5 \times 10^{-6} \) eV\(^2\) as an example. The expression (4) for \( P \) then reduces to

\[
P(\bar{\nu}_\mu \rightarrow \nu_\tau) \simeq \sin^2(\mu Br). \quad (5)
\]

The phase in \( P \) can be of the order of unity if \( \mu Br = \frac{\pi}{2} \) or if \( \mu Br > 1 \) for a constant \( B \). Evidently, this \( P \) is independent of \( E \). According to Eq. (1), the \( B_{AGN} \) varies with distance so that to have maximal depth of precession, we need to integrate the strength of the magnetic field along the neutrino trajectory. Thus, we require

\[
\int_0^r dr' B(r') \gtrsim \mu^{-1}. \quad (6)
\]

We note that Eq. (5) [alongwith Eq. (6)] give \( P(\bar{\nu}_\mu \rightarrow \nu_\tau) > 1/2 \) for the \( B_{AGN} \) profile given by Eq. (1) with \( \mu \sim 10^{-12} \mu_B \). Thus, an energy independent permutation (exchange) between \( \bar{\nu}_\mu \) and \( \nu_\tau \) may result with \( P > 1/2 \). This energy independent permutation of energy spectra of \( \bar{\nu}_\mu \) and \( \nu_\tau \) for small \( \delta m^2 \) follows from the fact that Eq. (5) also gives \( P(\nu_\tau \rightarrow \bar{\nu}_\mu) \) as we are considering a two neutrino state system. Let us further note that this small value of \( \delta m^2 (\delta m^2 \sim 5 \times 10^{-6} \) eV\(^2\)) is not only interesting in the context of SNP \([\Box]\) but also SN \([\Box]\).

b) \( \delta \sim \mu B \). Here \( \delta m^2 \) correspond to \( 5 \times 10^{-4} \) eV\(^2\). In this case expression (4) for \( P \) reduces to

\[
P(\bar{\nu}_\mu \rightarrow \nu_\tau) \simeq 1/2 \sin^2(\sqrt{2} \mu Br). \quad (7)
\]

Thus, for \( \delta m^2 \simeq 5 \times 10^{-4} \) eV\(^2\), energy dependent distortions may result in survived and precessed neutrino energy spectra with \( P \leq 1/2 \).

c) \( \delta \gg 2 \mu B \), that is, \( \delta m^2 \gg 5 \times 10^{-4} \) eV\(^2\). Energy dependent distortions may result for large \( \delta m^2 \) with \( P < 1/2 \). For instance, consider \( \delta m^2 \sim 10^{-3} \) eV\(^2\) relevant for atmospheric neutrino problem \([\Box]\). The result of vacuum oscillations with non vanishing vacuum mixing angle is a modification in the \( \bar{\nu}_\mu \) and \( \nu_\tau \) spectra through \( \bar{\nu}_\mu \rightarrow \nu_\tau \) or a modification in \( \nu_\mu \) and \( \nu_\tau \) spectra through \( \nu_\mu \rightarrow \nu_\tau \), whereas the magnetic moment effects give rise to changes in \( \nu_\mu \) and \( \nu_\tau \) spectra or in \( \bar{\nu}_\mu \) and \( \nu_\tau \) spectra. This simply follows from the fact that a Majorana type neutrino magnetic moment causes a precession between the relevant neutrino states of opposite helicity as well
as flavour in an external magnetic field. Thus, an empirical distinction between high energy \( \nu_e \) and \( \bar{\nu}_e \) spectra as well as between high energy \( \nu_\mu \) and \( \bar{\nu}_\mu \) spectra, if observed, will be an evidence for the magnetic moments effects here. The situation of \( \nu_e \to \nu_\tau \) may be realized by replacing \( \bar{\nu}_\mu \) by \( \bar{\nu}_e \) in Eq. (2) with the corresponding \( \delta m^2 \). A relevant remark is in order here: the deficit measured by superkamiokande in atmospheric muon neutrino flux may currently be explained either through \( \nu_\mu \to \nu_e \) or through \( \nu_\mu \to \nu_\tau \). For high energy neutrinos originating from AGNs, in the case of \( \nu_\mu \to \nu_e \), the ratio \( \nu_e/\nu_\mu \) is close to \( 1/2 \) as we take the \( \delta m^2 \) and the vacuum mixing angle suggested by recent superkamiokande data. Therefore, a ratio of \( \nu_e/\nu_\mu \) different from \( \sim 1/2 \) correlated to the direction of source may here provide an evidence for neutrino spin-flip in the AGN environment. Even for \( \nu_e/\nu_\mu \approx 1/2 \), a mutual comparison of relevant high energy neutrino flux spectra from various neutrino telescopes may be needed to unambiguously identify the cause of high energy neutrino conversions. In case of \( \nu_\mu \to \nu_\tau \), a measured ratio of \( \nu_\tau/\nu_\mu \) a deficit in an otherwise large \( \bar{\nu}_\mu \) flux is expected since now the precessed neutrino state is a sterile one. The sterile neutrinos do not interact weakly and therefore are accounted for by the disappearance/appearance of the relevant active neutrino (\( \bar{\nu}_\mu \)) flux. If the precessions are incomplete (as compared to complete permutations), the resulting high energy neutrino spectra are expected to be rather complicated combinations of the two neutrino species involved in the precession.

**Case 2.** \( V_G \neq 0 \) (with small \( \delta \), that is, \( \delta \ll 2\mu B \)). For constant \( V_G \), we obtain from Eq. (4) the relevant precession probability expression by replacing \( X \) with \( V_G \). If \( V_G \ll 2\mu B \) then using Eq. (1) and Eq. (3), we obtain \( \Delta f \ll 6 \cdot 10^{-32} \). We take here \( |\Delta f| \leq 10^{-34} \) as our criteria and so consequently the corresponding \( P \) reduces to (5). This results in \( P > 1/2 \) with no energy dependence. Thus this case coincides with case 1a) for small \( \Delta f \) depending on the given \( B_{AGN} \) profile. Consequently, if there is a violation of equivalence principle at the level of \( 10^{-34} \) or less, a spin (flavour)-precession for neutrinos may occur in the vicinity of AGN with small \( \delta m^2 \). Evidently, this value of \( \Delta f \) is independent of the gravity mixing angle \( \overline{B}_G \). For \( \Delta f \gg 10^{-34} \), energy dependence in \( P \) results with \( P \ll 1/2 \). For large \( \delta (\delta \approx V_G) \) see next case and if \( \delta \gg V_G \) then this case reduces to 1c). The upper bound for \( \Delta f \) obtained in this case has only a linear energy dependence, whereas the other necessary requirement [Eq. (6)] does not depend on \( E \) for small \( \delta \). This is in sharp contrast to the situation discussed in next case, where both the level crossing as well as the adiabaticity conditions depend on \( E \). Thus, to summarize, we have pointed out in this case that for high energy neutrinos originating from AGN, a spin (flavour)-precession may

\[
\Delta f \leq 6 \cdot 10^{-32}
\]
develop in the vicinity of AGN if $\Delta f \lesssim 10^{-34}$ and
for a reasonable choice of other parameters of the AGN model yielding $\nu_\tau/\bar{\nu}_\mu \gg 10^{-3}$.

**Case 3.** $V_G \simeq \delta$. This results in conversion effect in contrast to the previously considered two cases [which are spin (flavour)-precession effects].

Two conditions are essential for an adiabatic conversion: i) level crossing and ii) adiabaticity. The level crossing is obtained by equating the diagonal elements of the effective Hamiltonian in Eq. (2), that is, $V_G = \delta$. The level crossing for $E \sim 1$ PeV implies

$$10^{-39} \left( \frac{\delta m^2}{10^{-10} eV^2} \right) \lesssim \Delta f \lesssim 10^{-29} \left( \frac{\delta m^2}{1 eV^2} \right). \quad (8)$$

Note that relative sign between $\delta$ and $V_G$ is important for level crossing. From the level crossing it follows that $\Delta f \propto E^{-2}$, i.e., an inverse quadratic $E$ dependence on $\Delta f$. This level crossing is induced by an interplay of magnetic field and VEP. However, level crossing alone is not a sufficient condition for a complete conversion. As stated earlier, adiabaticity is the other necessary condition that determines the extent of conversion. If there is only level crossing and no adiabaticity at the level crossing then there is no conversion of antinuon neutrinos into tau (sterile) neutrinos. The relevant adiabaticity condition may be written as

$$B_{ad} \gtrsim 3 \cdot 10^2 G \left( \frac{\Delta f}{10^{-29}} \right)^{\frac{1}{2}} \left( \frac{10 R_S}{r} \right). \quad (9)$$

We note that $B_{ad} \lesssim B_{AGN}$ for $10 < x < 100$ with $\mu \sim 10^{-12} \mu_B$. Thus, the adiabatic conversion may occur giving rise to energy dependent distortions with corresponding conversion probability greater than 1/2. For large $\delta$ whereas a spin (flavour)-precession is suppressed [see case 1b) and 1c)], an adiabatic conversion may result with $P > 1/2$ for large $\Delta f$ (see Fig. 1). Let us emphasize that this adiabatic level crossing is induced by the change in the gravitational potential rather than the change in effective matter density. Thus, observationally, we may obtain here $\nu_\tau/\bar{\nu}_\mu \gtrsim 1$ due to an adiabatic conversion induced by an interplay of $V_G$ and $B_{AGN}$ in the vicinity of the AGN. For $\delta \ll V_G$ this case reduces to case 2 whereas for $\delta \gg V_G$, we obtain case 1c).

![Figure 1. $P(\bar{\nu}_\mu \to \nu_\tau)$ Vs $E$ including the effect of possible nonadiabaticity.](image)

It follows from the discussion in case 3 that a nonzero $\Delta f$ is needed to induce an adiabatic level crossing with $P > 1/2$. It is in contrast to cases 1 and 2 where a spin-flip may occur through spin (flavour)-precession without $\Delta f$ with $P > 1/2$.

### 4. RESULTS AND DISCUSSION

1. The initial fluxes of the high energy neutrinos originating from AGN are estimated to have the following ratios: $\nu_e/\nu_\mu \simeq 1/2$, $\nu_\tau/\bar{\nu}_\mu \lesssim 10^{-3}$. Thus, if an enhanced $\nu_\tau/\bar{\nu}_\mu$ ratio (as compared to no precession/conversion situation) is observed correlated to the direction of source for high energy neutrinos, then it may be either an evidence for a spin-flip through spin (flavour)-precession alone or through a resonant conversion in the vicinity of AGN due to an interplay of VEP and $B_{AGN}$ depending on the finer details of the relevant high energy AGN neutrino spectra. The spin (flavour)-precession and/or conversion effects discussed in this study may be distinguished by observing the energy dependence of the high energy neutrino flux profiles. A mutual comparison of
the relevant (that is, $\bar{\nu}_\mu$ and $\nu_\tau$) high energy neutrino spectra may in principle isolate the mechanism of neutrino conversions in the vicinity of AGN.

2. For small $\delta m^2$ ($\delta m^2 < 5 \cdot 10^{-6} \text{ eV}^2$) a spin (flavour)-precession may result in an energy independent permutation of the relevant neutrino spectra with the corresponding spin (flavour)-precession probability greater than 1/2. This spin (flavour)-precession may occur for small $\Delta f$ ($\Delta f \lesssim 10^{-34}$). The spin-flip may occur through resonant conversions induced by the VEP and $B_{\text{AGN}}$ as well. Assuming that the information on $\Delta f$ may be obtained from various terrestrial/extraterrestrial experiments, a mutual comparison between the survived and transformed high energy AGN neutrinos may enable one to distinguish the mechanism of conversion. If for small $\delta m^2$ ($\delta m^2 < 5 \cdot 10^{-6} \text{ eV}^2$), an energy dependent permutation between $\bar{\nu}_\mu, (\bar{\nu}_e)$ and $\nu_\tau$ are obtained empirically with corresponding $P > 1/2$ then this situation may be an evidence for a conversion effect due to an interplay of VEP and $B_{\text{AGN}}$.

For large $\delta m^2$ ($\Delta f > 10^{-34}$), if energy dependent distortions (and a change in $\nu_\tau/\bar{\nu}_\mu$) is observed with the corresponding conversion probability greater than 1/2 then the cause may be a relatively large $\Delta f$ ($\Delta f > 10^{-34}$). Thus, with the improved information on $\Delta f$ the cause of the conversion effect may be isolated. Further, as the energy span in the relevant high energy AGN neutrino spectra is several orders of magnitude, therefore, energy dependent spin (flavour)-precession/conversion probabilities may result in distortions in some part(s) of the spectra for relevant neutrino species and may thus be identifiable in existing/future high energy neutrino telescopes.

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