Neutrino Spin-Flip Effects in Active Galactic Nuclei

M. Anwar Mughal[1] and H. Athar[2*]

[1]*Department of Physics, Quaid-i-Azam University, Islamabad 45320, Pakistan*
[2]*Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan 300, R.O.C.*
and
Institute of Physics, National Chiao-Tung University, Hsinchu, Taiwan 300, R.O.C.

(Received November 20, 2001)

We study the effects of neutrino spin-flips in the magnetic field, B_{AGN}, of an active galactic nuclei (AGN) for high-energy neutrinos ($E \geq 10^6$ GeV) originating from the AGN, induced by an interplay of a violation of the equivalence principle parameterized by Δf and the twist in B_{AGN}. We point out that a conversion effect may exist for $\Delta f \sim 10^{-34}(\delta m^2/10^{-5} \text{ eV}^2)$ independent of the gravity mixing angle. Observational consequences for this conversion effect are discussed.

PACS. 95.85.Ry – Neutrino, muon, pion, and other elementary particles; cosmic rays.
PACS. 98.54.Cm – Active and peculiar galaxies.
PACS. 14.60.Pq – Neutrino mass and mixing.

I. Introduction

In this paper, we study the spin-flip effects for high-energy neutrinos ($E \geq 10^6$ GeV) originating from active galactic nuclei (AGN) induced by a violation of the equivalence principle (VEP) and/or magnetic field twist; AGNs are presently considered to be a likely source of high-energy neutrinos [1]. The VEP arises because different flavors of neutrinos may couple differently to gravity [2-4]. This essentially results from the realization that flavor eigenstates of neutrinos may be the admixture of the gravity eigenstates of neutrinos with different gravitational couplings. A magnetic field twist occurs when the direction of the magnetic strength lines in the plane transverse to the neutrino momentum originating from AGN may not be fixed. Several general descriptions of the possible effects of magnetic field twist are available [5], as well as those related to the sun [6], supernovae [7] and the early universe [8].

The present study is particularly welcome as the new under ice or water Cerenkov light detector arrays, namely AMANDA, Baikal (as well as NESTOR and ANTARES), commonly known as high-energy neutrino telescopes, based on muon detection, will have not only energy, angle and flavor resolution but also possibly particle and antiparticle resolution in the electron neutrino channel near the Glashow resonance energy, $E \sim 6.4 \cdot 10^6$ GeV [9-12]. These characteristics make these neutrino telescopes especially suitable for the study of high-energy neutrino conversions.

We study here the spin-flip effect 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 streams out from the core in a transverse plane and produces hot spots when the jet strikes

the surrounding matter at its ends. For a discussion of neutrino spin-flips in jets and hot spots, see [13]. Previously, the spin-flip effects for AGN neutrinos due to the VEP were studied in [14, 15]. The VEP is parameterized by a dimensionless parameter Δf. In [14], by demanding an adiabatic conversion to occur, a lower bound on the neutrino magnetic moment μ was obtained in terms of Δf, whereas in [15], the effect of a possible random fluctuation in the magnetic field of the AGN, B_{AGN}, on the neutrino spin precession was considered. In [16], neutrino spin-flips in AGN due to gravitational effects (not due to the VEP) and due to the presence of a magnetic field were studied. Here we address two aspects of spin-flip for high-energy neutrinos originating from AGNs, viz., the spin (flavor)-precession with (or without) VEP and the twist in B_{AGN}; and the adiabatic/non-adiabatic conversion due to an interplay of twist in B_{AGN} and the VEP. We point out that, for the latter type of conversion effect, a Δf on the order of $10^{-39} - 10^{-29}$ depending on δm^2 gives reasonably large conversion probabilities. In particular, we point out that the neutrino spin-flip in an AGN induced by an interplay of the VEP and the twist in B_{AGN} may give rise to *changes* in the particle/antiparticle ratio as compared to the no spin-flip situation in the electron neutrino channel near the Glashow resonance energy.

The plan of the rest of the paper is as follows. In section II, we briefly discuss the matter density and a magnetic field profile in an AGN. In section III, we discuss the spin (flavor)-precession due to the VEP and determine the value of Δf needed to have the precession probability greater than 1/2. In the same section, we consider in some detail the adiabatic and non-adiabatic conversions induced by an interplay of a conceivable twist in B_{AGN} and the VEP and estimate the resulting neutrino spin (flavor)-conversion probabilities. In section IV, we discuss a possible observational consequence of neutrino spin-flip in an AGN and contrast it with the pure vacuum flavor oscillations. Finally in section V, we summarize our results.

II. The matter density and magnetic field in an AGN

Neutrino spin-precession in the context of the sun was discussed in [17]. It was pointed out that the matter effects tend to suppress the neutrino spin-precession effect. As shown below, for an AGN, matter effects arising due to coherent forward scattering of neutrinos off the matter particle background are negligible [1]. The essential conditions needed for appreciable spin-precession are: (i) $\mu B \Delta r \gtrsim 1$, i.e., B must be large enough in the region of width Δr; (ii) the smallness of the 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 the typical observed intergalactic magnetic field for the nearby galaxies is estimated to be $\sim O(10^{-9})$ G at a scale of Mpc, where 1 pc $\sim 3 \cdot 10^{18}$ cm [19]. Taking a typical distance between the earth and the AGN as $\sim O(10^2)$ Mpc, we note that the effect induced by the intergalactic and galactic magnetic fields is quite small as the galactic magnetic field is $\sim O(10^{-6})$ G, thus causing negligible reverse neutrino spin-precession.

According to [20], the matter density in the vicinity of an AGN has the following profile: $\rho(x) = \rho_0 f(x)$, where $\rho_0 \simeq 1.4 \cdot 10^{-13}$ g/cm^3 and $f(x) \simeq x^{-2.5}(1 - 0.1x^{0.31})^{-1}$, as we take the AGN photon luminosity to be 10^{46} erg/s, with $x \equiv r/R_S$, R_S being the Schwarzchild radius

---

[1] Similar estimate for other astrophysical systems like sun and supernovae shows that the matter effects are indeed non-negligible in most parts of these systems [18].

of the AGN: $R_S \simeq 3 \cdot 10^{13} \left(\frac{M_{AGN}}{10^8 M_\odot} \right)$ cm. We take the distance traversed by the neutrinos to be $10 < x < 100$ in the vicinity of the 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 neutrino spin-flip, on the other hand, is $l_0 \equiv \sqrt{2}\pi m_N G_F^{-1} \sim 2 \cdot 10^9$ g/cm$^2 \gg l_{AGN}$. Hence, from now on, we ignore the matter effects.

We consider now the magnetic field in the vicinity of the AGN with the following profile [20]

$$B_{AGN}(x) = B_0 g(x), \tag{1}$$

where $B_0 \sim 5.5 \cdot 10^4$ G and $g(x) = x^{-1.75}(1 - 0.1x^{0.31})^{-0.5}$ for $10 < x < 100$. We will use this B_{AGN} in our estimates as an example.

III. Neutrino spin-flip due to the VEP and twist in B_{AGN}

The evolution equation for the two neutrino state for vanishing gravity and vacuum mixing angles may be written in a frame rotating with the magnetic field as [21]

$$i\dot{\psi} = H_{eff}\psi, \tag{2}$$

where $\psi^T = (\nu_e, \bar{\nu}_\alpha)$ and H_{eff} is a 2×2 matrix with $H_{11} = 0$, $H_{12} = H_{21} = \mu B$ and $H_{22} = \delta - V_G + \dot{\phi}$. Here $\alpha = \mu$ or τ, and $\dot{\phi} \equiv d\phi/dr$ defines the direction of rotation of $B_{AGN}(\equiv B)$ in the plane orthogonal to the neutrino momentum. $\delta = \delta m^2/2E$, where $\delta m^2 = m_j^2 - m_1^2 > 0$, with E being the neutrino energy and $j = 2$ or 3. In Eq. (2), for later convenience, we have subtracted from the lower diagonal element, the upper diagonal element of the effective Hamiltonian in order to make the upper diagonal element equal to zero. This is equivalent to the renormalization of the two neutrino wave functions by the same factor, which does not change the relevant precession (conversion)/survival probabilities [21]. V_G is the effective potential felt by the neutrinos at a distance r from a gravitational source of mass M due to the VEP and in its rather simpler form is given by [2]

$$V_G \equiv \Delta f \beta(r) E, \tag{3}$$

where $\Delta f = (f_\alpha - f_1)(f_\alpha + f_1)^{-1}$ and $\beta(r) = G_N M r^{-1}$ is the gravitational potential in the Keplerian approximation, with G_N being the gravitational constant. Here $f_1 G_N$ and $f_\alpha G_N$ are the gravitational couplings respectively for ν_e and $\bar{\nu}_\alpha$, such that $f_1 \neq f_\alpha$. Let us note that in the vicinity of an AGN, the V_G due to the AGN dominates [22].

We consider mainly the following two neutrino flavors: ν_e and ν_τ in the subsequent discussion in this section, motivated by the fact that the initial fluxes of these neutrino states are estimated to be maximally asymmetric, typically with $(\nu_\tau + \bar{\nu}_\tau)/(\nu_e + \bar{\nu}_e) \gtrsim 10^{-5}$, according to various models of AGN [23]. Presently, the high-energy neutrino flux from AGNs can dominate over the atmospheric neutrino background typically for $E \geq 10^6$ GeV. The current empirical upper bounds on high-energy neutrino flux, for instance, from AMANDA (B10), is relevant typically for $E \cdot 10^6$ GeV [24]. Let us mention here that the upper bound discussed in [25] does not apply to the (diffuse) high-energy neutrino flux originating from the cores of AGNs because these sources do not contribute dominantly to the observed ultrahigh-energy cosmic ray flux.

In this section, we intend to discuss, in some detail the possible effects arising due to the interaction of the neutrino magnetic moment, μ, with B_{AGN}, which enhance the ratio, that is, to obtain $(\nu_\tau + \bar{\nu}_\tau)/(\nu_e + \bar{\nu}_e) \gg 10^{-5}$. In this context, we now propose to study the various main possibilities arising from the relative comparisons between δ, V_G and $\dot{\phi}$ in Eq. (2).

Case 1. $V_G = \dot{\phi} = 0$. For constant B, we obtain the following expression for the spin-flavor precession probability $P(\nu_e \to \bar{\nu}_\alpha)$ by solving Eq. (2):

$$P(\nu_e \to \bar{\nu}_\alpha) = \left[\frac{(2\mu B)^2}{(2\mu B)^2 + X^2}\right] \sin^2\left(\sqrt{(2\mu B)^2 + X^2} \cdot \frac{\Delta r}{2}\right), \tag{4}$$

with $X = \delta$. We now discuss the relative comparison between $2\mu B$ and δ, and evaluate P for the corresponding δm^2 range.

a) $\delta \ll 2\mu B$. Using the B given in Eq. (1) for $\mu \sim 10^{-12}\mu_B$ [26], the condition $\delta \ll 2\mu B$ implies $\delta m^2 \ll 5 \cdot 10^{-4}$ eV^2 with $E \sim 10^6$ GeV. We take here $\delta m^2 \sim 5 \cdot 10^{-6}$ eV^2 as an example. The expression (4) for P then reduces to

$$P(\nu_e \to \bar{\nu}_\alpha) \simeq \sin^2(\mu B \Delta r). \tag{5}$$

The phase of P can be of the order of unity if $\mu B \Delta r = \frac{\pi}{2}$ (or if $\mu B \Delta r \gtrsim 1$) 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 spin-flavor precession, we need to integrate the strength of the magnetic field along the neutrino trajectory. Thus, for maximal depth of the $\nu_e \to \bar{\nu}_\alpha$ precession, we require in Eq. (5) that

$$\mu \int_0^{r'} dr' B(r') \gtrsim 1. \tag{6}$$

We note that Eq. (5) [along with Eq. (6)] give $P(\nu_e \to \bar{\nu}_\alpha) > 1/2$ for the B_{AGN} profile given by Eq. (1) with $\mu \sim 10^{-12}\mu_B$. Thus, an energy independent permutation (exchange) between ν_e and $\bar{\nu}_\alpha$ may result with $P > 1/2$. This energy *independent* permutation of the energy spectra of ν_e and $\bar{\nu}_\alpha$ for small δm^2 follows from the fact that Eq. (5) also gives $P(\bar{\nu}_\alpha \to \nu_e)$, since we are considering a two neutrino state system. For another magnetic field strength profile of the AGN [27] we obtain $P(\nu_e \to \bar{\nu}_\alpha) > 1/2$ for $\mu \sim 2 \cdot 10^{-16}\mu_B$ [this profile suggests a constant magnetic field $\sim O(10^4)$ G for $x \gtrsim 10$]. We thus obtain the same P value ($P > 1/2$) with a 4 orders of magnitude smaller μ for this B_{AGN} profile for the same δm^2. Therefore, if μ turns out to be $\sim O(10^{-16})\mu_B$ and if empirically it is found that, for instance, $P(\nu_e \to \bar{\nu}_\tau) > 1/2$ for small δm^2 then this situation may be an evidence for the latter B_{AGN} profile. Let us further note that this small value of δm^2 ($\delta m^2 \sim 5 \cdot 10^{-6}$ eV^2) is not only interesting in the context of sun [6] but also supernovae [7].

b) $\delta \simeq 2\mu B$. Here δm^2 corresponds to $5 \cdot 10^{-4}$ eV^2. In this case expression (4) for P reduces to

$$P(\nu_e \to \bar{\nu}_\alpha) \simeq 1/2 \sin^2(\sqrt{2}\mu B \Delta r). \tag{7}$$

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

c) $\delta \gg 2\mu B$, that is, $\delta m^2 \gg 5 \cdot 10^{-4}$ eV^2. Energy dependent distortions may result for relatively large δm^2 with $P < 1/2$. For instance, consider $\delta m^2 \sim 10^{-3}$ eV^2, relevant for the atmospheric neutrino problem [28]. The $(\nu_e + \bar{\nu}_e)/(\nu_\tau + \bar{\nu}_\tau)$ ratio as well as $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ will have energy dependence in this case. Among the ν_μ and ν_τ channels, the spin-flavor precessions lead to an energy dependent $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu)$. This situation may be realized by replacing ν_e by ν_μ and α by τ in Eq. (2) with the corresponding changes in δm^2 and in V_G. For comparison, let us note that the pure vacuum flavor oscillations lead to an energy independent ratio equal to 1/2, that is, $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu) \sim 1/2$ [29]. Therefore, an energy dependent ratio different from 1/2 may provide evidence for a high-energy neutrino spin-flip in AGN. It is relevant here to mention that the future/existing high-energy neutrino telescopes may attempt to measure the three ratios $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu)$, $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu)$ as well as $(\nu_\tau + \bar{\nu}_\tau)/(\nu_e + \bar{\nu}_e)$ of the absolute fluxes of high-energy neutrinos and possibly the energy dependence in this ratio [see section IV for some further discussion].

Let us note that all these spin (flavor)-precession situations are realized without any VEP and magnetic field twist in B_{AGN}, as a spin (flavor)-precession for AGN neutrinos may develop even without a VEP and gravitational neutrino flavor dependent effects. Thus, the cause of change (as compared to the no precession situation) in the ratios of the $(\nu_\tau + \bar{\nu}_\tau)$, $(\nu_\mu + \bar{\nu}_\mu)$ and $(\nu_e + \bar{\nu}_e)$ fluxes, as well as an energy dependence in these ratios, in future/existing high-energy neutrino telescopes may not only be attributed to VEP and/or gravitational effects depending on the relevant δm^2 range.

Case 2. $V_G = 0$, $\dot{\phi} \neq 0$. For constant B and $\dot{\phi}$, we obtain the expression for the precession probability (for small δ) by substituting $\dot{\phi}$ for X in Eq. (4). We first take $\dot{\phi} \sim 2\mu B$, thus $\delta \ll \dot{\phi}$ for $\delta m^2 \sim 5 \cdot 10^{-6}$ eV^2 [as considered in case 1a)]. Note that in this expression for precession probability, the sign of $\dot{\phi}$ is unimportant. It is natural to suggest that the total rotation angle of the AGN magnetic field is restricted by $\Delta \phi \gtrsim \pi$. Thus, for instance, a twist appears, when high-energy neutrinos cross the toroidal magnetic field with magnetic strength lines winding around the spherically accreting matter disk in the AGN. In this case the maximal rotation angle is π, i.e., the above bound is satisfied. The field twist can be characterized by the scale of the twist, r_ϕ, such that $r_\phi \equiv \pi/\dot{\phi}$, so that on the way, the total rotation angle (for uniform rotation), is $\Delta \phi = \pi$. Let us define the critical rotation scale as $r_\phi^c \equiv \pi/2\mu B$ [30]. Note that this r_ϕ^c coincides with the precession length l_p $[\equiv (2\mu B)^{-1}]$ apart from a factor of π and, on dimensional grounds, is the simplest possibility. For appreciable magnetic field twist effects, evidently we require $r_\phi \gtrsim r_\phi^c$. Comparing r_ϕ^c with the distance from the center of AGN in units of x (or R_S), we find that $r \sim r_\phi^c$ for a B that is smaller than the available B_{AGN} given by Eq. (1). In this case $P(\nu_e \to \bar{\nu}_\alpha)$ reduces to Eq. (7). Thus, for small δm^2, we obtain here $P \gtrsim 1/2$. This case can therefore be differentiated from the previous one by concentrating on the P value. For small δm^2 [case 1a)] previously we have $P > 1/2$. The magnetic field twist effects here may give rise to an energy independent spin (flavor)-precession between ν_e and $\bar{\nu}_\tau$. However, here, unlike the previous case for small δm^2, the required B has an upper bound for a naturally scaled field twist. For $\dot{\phi} \ll 2\mu B$, we obtain case 1a) whereas for $\dot{\phi} \gg 2\mu B$, we obtain case 1c).

For $\delta \sim -\dot{\phi}$, the spin (flavor)-precession results from a cancellation between δ and $\dot{\phi}$ which for a naturally scaled $\dot{\phi}$ corresponds to $\delta m^2 \gtrsim 5 \cdot 10^{-4}$ eV^2 with $P > 1/2$, whereas the opposite sign of $\dot{\phi}$ results in suppression of P. Thus, for large δm^2 (but comparable to $\dot{\phi}$), energy dependent distortions may occur with $P > 1/2$. For $\delta \gg \dot{\phi}$, this case reduces to case 1c).

Case 3. $V_G \neq 0$, $\dot\phi = 0$ (with small δ, that is, $\delta \ll 2\mu B$). For constant V_G and B, 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 $\Delta f \ll 6\cdot10^{-32}$. We take here $|\Delta f| \gtrsim 10^{-34}$ 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 $\Delta f\,(\gtrsim 10^{-34})$, depending on the given B_{AGN} profile. Consequently, if there is a VEP at the level of 10^{-34} or less, a spin (flavor)-precession for neutrinos may occur in the vicinity of AGN with small δm^2. Evidently, this value of Δf is independent of the gravity mixing angle [2]. Let us note in passing that this value of Δf is (much) lower than the one obtained in [4]. For $\Delta f \gtrsim 10^{-34}$, energy dependence in P results in $P \gtrsim 1/2$. For large δ ($\delta \simeq V_G$) see case 5, and if $\delta \gg V_G$ then this case reduces to 1c). The upper bound for Δf obtained in this case has only a linear energy dependence, whereas the other necessary requirement [Eq. (6)] does not depend on E for small δ. This is in sharp contrast to the situation discussed in case 5, 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 (flavor)-precession may develop in the vicinity of the AGN if $\Delta f \gtrsim 10^{-34}$ yielding, for instance, $(\nu_\tau + \bar\nu_\tau)/(\nu_e + \bar\nu_e) \gg 10^{-5}$.

The observational consequences of the high-energy neutrino spin-flavor precessions discussed in the previous three cases are the energy dependence in the relevant ratio of the fluxes as well as a possible change in the ratios with respect to the pure vacuum flavor oscillations. With the improved information on the relevant neutrino mixing parameters, these cases may in principle be disentangled from each other.

Case 4. $V_G = \dot\phi$ (for small δ). This results in conversion effect in contrast to the previously considered three cases [which are spin (flavor)-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 element of the effective Hamiltonian in Eq. (2), i.e., $V_G = \dot\phi$ implying $\Delta f \propto E^{-1}$ (or a *linear* dependence of $\dot\phi$ on E). For $\bar\nu_e \to \nu_\alpha$ conversions, if $\Delta f > 0$ (both for particles and antiparticles) then there is no level crossing as $\dot\phi$ is negative for this channel. If $\Delta f < 0$, then the level crossing shifts to the antiparticle channel ($\bar\nu_e \to \nu_\alpha$). Thus, a simultaneous deficit/enhancement in both the ν_e and $\bar\nu_e$ spectra (and in the ν_τ and $\bar\nu_\tau$ spectra) is not expected due to an interplay of the VEP and the twist in B_{AGN} unless Δf has a different sign for particles and antiparticles. The level crossing is induced by a naturally scaled field twist for $\Delta f \gtrsim 10^{-34}$, that is, when $r_\phi^c/r \gtrsim 1$ (see case 2 also). Let us note that this level crossing is induced by an interplay of magnetic field twist and a VEP for neutrinos with small δm^2 ($\delta m^2 < 5\cdot10^{-6}$ eV^2). This is a characteristically distinct feature of a more realistic situation of having magnetic strength lines winding around the nearly spherical matter disk. 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 electron neutrinos into anti-tau neutrinos. In the remaining part of this case, we discuss quantitatively the latter condition, that is, adiabaticity.

The adiabaticity condition assumes the slowness of variation in V_G and is given by [31]:
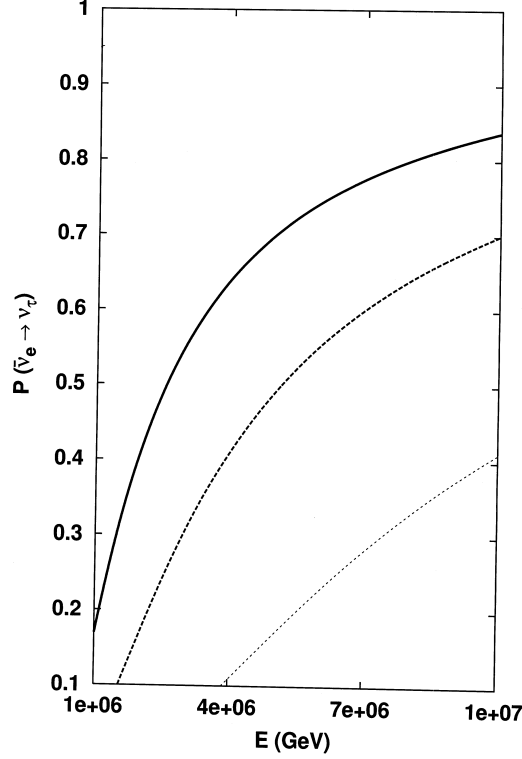
$$\cdot\, R = \frac{2(2\mu B)^2}{|\dot V_G|}.$$

(8)

FIG. 1. $P(\bar{\nu}_e \to \nu_\tau)$ as a function of E (GeV) for some representative values of Δf with $\delta m^2 \sim 10^{-10}$ eV^2 and $\mu \sim 10^{-12} \mu_B$ using Eq. (9) for illustrative purpose. Upper curve, $\Delta f \sim 10^{-29}$, middle curve, $\Delta f \sim 5 \cdot 10^{-30}$, lower curve, $\Delta f \sim 2 \cdot 10^{-30}$.

This is the adiabaticity parameter in the resonance for uniform magnetic field twist ($\ddot{\phi} = 0$). A conversion is adiabatic if $\cdot_R \gtrsim 1$. Notice that here $\cdot_R \propto E^{-1}$. Since $\cdot_R$ depends (quadratically) on B, thus adiabaticity of conversion is essentially determined and controlled by the given B profile. By requiring an adiabatic conversion to occur, we can obtain B_{ad} from Eq. (8). Using Eq. (1) and for $\Delta f \sim 10^{-34}$ (a requirement of level crossing), we obtain $B_{\mathrm{ad}} < B_{AGN}$. It is interesting to note that the B_{ad} does not depend on any B profile of the AGN, it is determined rather by the gradient of V_G. Thus, an adiabatic conversion may occur for $\Delta f \sim 10^{-34}$ or less depending on δm^2 in a uniform magnetic field twist. Let us emphasize that this adiabatic level crossing is induced by the change in the gravitational potential rather than the change in the effective matter density. A general expression for neutrino spin-flavor conversion probability including the effect of non adiabaticity ($\cdot_R < 1$), using Eq. (2), is [32]

$$P(\bar{\nu}_e \to \nu_\tau) = \frac{1}{2} - \left\{ \frac{1}{2} - \exp\left(-\frac{\pi}{2} \cdot_R \right) \right\} \cos 2\theta_{B_i} \cos 2\theta_{B_f}, \qquad (9)$$

where $\tan 2\theta_{B_i} = (2\mu B)/(\delta - V_G)$ is evaluated at the high-energy neutrino production site in the vicinity of the AGN and $\tan 2\theta_{B_f} = (2\mu B)/(\delta - V_G)$ is evaluated at the exit. In Fig. 1, we display P using Eq. (9) for some representative values of Δf, with $\delta m^2 \sim 10^{-10}$ as a function

of E for illustrative purpose only. From Fig. 1, we notice that for $E \sim 6.4 \times 10^6$ GeV, the P is rather large ($\sim 0.6 - 0.7$), thus leading to a suppression in the $\bar{\nu}_e$ flux.

Nonuniform field twist ($\ddot{\phi} \neq 0$) changes the adiabaticity condition (8). It now reads

$$\cdot_\phi = \frac{2(2\mu B)^2}{|\dot{V}_G - \ddot{\phi}|}. \tag{10}$$

Thus, for $\ddot{\phi} \simeq \dot{V}_G$, we may have a large enhancement in $\cdot_\phi$. For a naturally scaled field twist, the total rotation angle for a nonuniform magnetic field twist is given by [7]

$$\Delta\phi \sim \cdot_R^{-1}, \tag{11}$$

i.e., the total rotation angle is given by the inverse of the adiabaticity parameter for a uniform magnetic field twist. Clearly, only modest improvement in $\cdot_R$ may be achieved for a naturally scaled magnetic field twist. The corresponding conversion probability P in this case is energy dependent. Thus, observationally, we may obtain here $(\nu_\tau + \bar{\nu}_\tau) \sim (\nu_e + \bar{\nu}_e)$, due to an adiabatic conversion induced by an interplay of $\dot{\phi}$ and V_G in the vicinity of the AGN. For large δ, comparable to V_G and $\dot{\phi}$, see case 6.

Case 5. $V_G \simeq \delta, \dot{\phi} = 0$. This situation also results in conversion effects (as opposed to cases 1-3), however see case 3 also. The level crossing implies

$$\Delta f \simeq 2 \cdot 10^{-34} \left(\frac{\delta m^2}{10^{-5} eV^2} \right). \tag{12}$$

Note that the relative sign between δ and V_G is important for level crossing.

If $\Delta f > 0$, both for particles and antiparticles, then both ν_e and $\bar{\nu}_e$ will transform simultaneously, whereas if $\Delta f < 0$, both for particles and antiparticles, no level crossing takes place. On the other hand, if Δf changes sign for particles and antiparticles, level crossing between particles *or* antiparticles will take place. Thus, this case can be distinguished from the previous case.

It is important to note that from the level crossing it follows that $\Delta f \propto E^{-2}$, i.e., an inverse quadratic E dependence on Δf. Thus, the level crossing induced by the VEP alone has a *different* energy dependence on Δf, as compared to the level crossing induced by an interplay of $\dot{\phi}$ and the VEP (see previous case). The relevant adiabaticity condition may be written as

$$B_{\mathrm{ad}} \gtrsim 3 \cdot 10^2 \mathrm{G} \left(\frac{10^{-12}\mu_B}{\mu} \right) \left(\frac{\Delta f}{10^{-29}} \right)^{\frac{1}{2}} \left(\frac{10 R_S}{r} \right). \tag{13}$$

We note that $B_{\mathrm{ad}} \lesssim B_{AGN}$ for $10 < x < 100$. The adiabaticity parameter here has the *same* energy dependence on E as in case 4. Thus, the adiabatic conversion may occur, giving rise to energy dependent distortions with corresponding conversion probability greater than 1/2. For large δ whereas a spin (flavor)-precession is suppressed [see case 1b) and 1c)], an adiabatic conversion may result with $P > 1/2$ for large Δf, thus resulting in correspondingly different observational consequences. For $\delta \ll V_G$ this case reduces to case 3, whereas for $\delta \gg V_G$, we obtain case 1c).

It follows from the discussion in cases 4 and 5 that a *nonzero* Δf is needed to induce an adiabatic level crossing with $P > 1/2$. This is in contrast to cases 1, 2 and 3 where a spin-flip may occur through spin (flavor)-precession without Δf with $P > 1/2$.

Case 6. If δ, V_G and $\dot{\phi}$ are of the same order of magnitude then we have two possibilities: the V_G and $\dot{\phi}$ terms cancel each other. Then, effectively case 1 a) is recovered. On the other hand, if V_G and $\dot{\phi}$ tend to add up, then effectively (apart from a factor of 2) we obtain either case 2 or case 5.

From the discussion in the previous cases, it follows that neutrino spin-flavor precessions/conversions may occur in several situations depending on the range of relevant neutrino mixing parameters.

IV. Possible observational consequences of neutrino spin-flip in AGN

In this section, we discuss in some detail the potential of the future high-energy neutrino telescopes to possibly determine some observational consequences of neutrino spin-flip in AGN through examples.

The planned high-energy neutrino telescopes may in principle differentiate between the three neutrino flavors (e, μ and τ) considered so far in this paper [10]. The particular relevance here is of the electron neutrino channel, in which the downward going $\bar{\nu}_e$ interaction rate (integrated over all angles) is estimated to be an order of magnitude higher than that of ($\nu_e + \bar{\nu}_e$) per Megaton per year at $E \sim 6.4 \cdot 10^6$ GeV [33]. This order of magnitude difference in the interaction rate of downward going $\bar{\nu}_e$ relative to ($\nu_e + \bar{\nu}_e$) deep inelastic scatterings is due to the Glashow resonance encountered by $\bar{\nu}_e$ with $E \gtrsim 10^6$ GeV when they interact with electrons near or inside the detector. The upward going $\bar{\nu}_e$, on the other hand, while passing through the earth, at these energies, are almost completely absorbed by the earth. Thus, for instance, if $E \sim 6.4 \cdot 10^6$ GeV, an energy resolution $\Delta E/E \sim 2\Gamma_W/M_W \sim 1/20$, where $\Gamma_W \sim 2$ GeV is the width of Glashow resonance and $M_W \sim 80$ GeV, may be needed to empirically differentiate between ν_e and ($\nu_e + \bar{\nu}_e$). The $\bar{\nu}_e$ and ($\nu_e + \bar{\nu}_e$) essentially produce a single shower event. Thus, the planned high-energy neutrino telescopes may in principle attempt to measure the $\nu_e/\bar{\nu}_e$ ratio near the Glashow resonance energy in addition to identifying ($\nu_\tau + \bar{\nu}_\tau$), ($\nu_\mu + \bar{\nu}_\mu$) as well as ($\nu_e + \bar{\nu}_e$) events separately by measuring the ratio of these fluxes. This may allow us to corroborate the neutrino mixing effects somewhat meaningfully.

The near future large high-energy neutrino telescopes may attempt to utilize this enhancement in the $\bar{\nu}_e$ cross-section over that of the electrons to measure the high-energy (antielectron) neutrino flux. Therefore, it is useful to ask for what possible range of neutrino mixing parameters, the high-energy $\bar{\nu}_e$ flux could be suppressed (or enhanced). In the remaining part of this section, we elaborate such a possibility. Let us remark here that at present the absolute normalization of the high-energy neutrino flux is basically unknown [34]. The suppression or enhancement for high-energy $\bar{\nu}_e$ flux correlated to the direction of the source along with the corresponding changes in the remaining neutrino flavors, as pointed out in this paper, depends only on the neutrino mixing parameters (and on the source).

Let us comment on the implications of current atmospheric and solar neutrino results on our analysis presented in section III. A recent global three neutrino oscillation study [35] of neutrino data indicates that the best fitted δm^2 and $\sin^2 2\theta$ values for solving the atmospheric neutrino problem in terms of $\nu_\mu \rightarrow \nu_\tau$ oscillations are typically $\sim 10^{-3}$ eV^2 and ~ 1. On the other hand, presently there exists more than one solution for solving the solar neutrino problem in terms of $\nu_e \rightarrow \nu_\alpha$ oscillations. For the SMA (MSW) solution, the δm^2 and $\sin^2 2\theta$ values are $\sim 10^{-5}$ eV^2 and $\sim 10^{-2}$, for the LMA (MSW) solution, these are $\sim 10^{-5}$ eV^2 and ~ 1, whereas for the VAC

solution, these are $\sim 10^{-10}$ eV^2 and ~ 1, respectively. The LOW solution values are close to that of the LMA (MSW) solution. Following [36], and using these values of δm^2 and $\sin^2 2\theta$, we note that *energy independent* pure vacuum neutrino flavor oscillations occur between the AGN and the earth irrespective of the specific oscillation solution for the solar neutrino problem.

In order to further contrast the spin-flip effects studied in this paper with the pure vacuum flavor oscillations for (downward going) high-energy neutrinos originating from AGNs, let us emphasize that vacuum flavor oscillations lead to the same energy independent ratio for the three flavors, i.e., $F_e : F_\mu : F_\tau = 1 : 1 : 1$, where $e \equiv (\nu_e + \bar{\nu}_e)$, etc., at the level of intrinsic electron neutrino flux F_e^0. This is so because, firstly, the matter effects are basically negligible in the vicinity of the yet known sources of high-energy neutrinos as well as between the source and the earth, and, secondly, the sources are considered to be cosmologically distant and that the intrinsic ratio of the high-energy neutrinos is $1 : 2 : 0$. Therefore, a deviation from $1 : 1 : 1$ for the final ratios correlated to the direction of the source as well as an energy dependence may provide an example of a neutrino spin-flip effect in AGN. A simple relevant remark is in order here. The pure vacuum flavor oscillation length is given by $l_f \sim 4E/\delta m^2$, whereas the spin-flavor precession length is (defined earlier as $l_{\rm p}$) $l_{sf} \sim 1/2\mu B$. For the δm^2 range under discussion, i.e., $10^{-10} \cdot \ \delta m^2/eV^2 \cdot \ 10^{-3}$, and for the typical E value range, i.e., $10^6 \cdot \ E/$GeV $\cdot \ 10^7$, with $\mu \sim 10^{-12} \mu_B$ and $B \equiv B_{AGN}$ given by Eq. (1), we note that $l_{sf} < l_f$. Therefore, spin-flip effects may dominate in the vicinity of the AGN. The pure vacuum flavor oscillations that may dominate between the AGN and the earth are essentially an energy independent effect. Thus the energy dependence due to neutrino spin-flip in AGN in for instance $(\nu_e + \bar{\nu}_e)/(\nu_\tau + \bar{\nu}_\tau)$ will survive, providing a signature of neutrino spin-flip in AGNs (see Fig. 1).

To disentangle the neutrino spin-flip effects from pure vacuum flavor oscillation effects, a suitable energy range $\sim 4M_W \Gamma_W/m_e$ can be centered at $E \sim 6.4 \times 10^6$ GeV. The vacuum neutrino flavor mixing parameters (namely δm^2 and $\sin^2 2\theta$) will presumably get measured in various terrestrial experiments and so the corresponding effects for high-energy neutrinos can reliably be isolated from the spin-flip effects discussed here.

In the case of spin-flavor precessions between $(\nu_\mu + \bar{\nu}_\mu)$ and $(\nu_\tau + \bar{\nu}_\tau)$, which may happen for the range of δm^2 values given in case 1c) of the previous section, the observational consequence is a change in the value of the $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu)$ ratio as compared to that of pure vacuum flavor oscillations along with a possible energy dependence. The empirical distinction between ν_μ and $\bar{\nu}_\mu$ as well as ν_τ and $\bar{\nu}_\tau$ is currently not envisaged for the typical high-energy neutrino telescopes. The spin-flavor precession effects discussed in cases 1-3 leads to precessions of the type $\nu_e \to \bar{\nu}_\mu, \bar{\nu}_\tau$ and $\bar{\nu}_e \to \nu_\mu, \nu_\tau$ simultaneously. Thus, in this case the ratio $\nu_e/\bar{\nu}_e$ is the same, however, energy dependence in the ratio $\nu_e/\bar{\nu}_e$ and a change in the non-electron neutrino flux ratios here remain a distinctive feature of spin-flavor precessions, depending on δm^2 values. The energy dependence in the $\nu_e/\bar{\nu}_e$ ratio due to production should be essentially absent in case ν_e and $\bar{\nu}_e$ come from the same parent particle, for instance, from μ.

There are several situations (case 4-5) as discussed in the previous section in which $\nu_e \to \bar{\nu}_\mu$, $\bar{\nu}_\tau$ spin-flavor conversions may occur. As pointed out earlier in this section, distinction between ν_e and $\bar{\nu}_e$ may become possible near the Glashow resonance energy, so this possibly gives a better chance to identify an observational consequence of neutrino spin-flip through spin-flavor conversions. For $\Delta f \sim 10^{-34}$, if the VEP is different for neutrinos and antineutrinos then the energy dependent spin-flavor conversions, as discussed in case 5, may give rise to change in the $\nu_e/\bar{\nu}_e$ ratio, in addition to a change in $(\nu_\tau + \bar{\nu}_\tau)$ or $(\nu_\mu + \bar{\nu}_\mu)$, whichever the case may be.

However, if the VEP is the same for neutrinos and antineutrinos, then this situation coincides with the previous situation of spin-flavor precession, i.e., no change in the $\nu_e/\bar{\nu}_e$ ratio. Thus, for instance, absence (or enhancement, depending on sign of Δf) of $\bar{\nu}_e$ events near the Glashow energy and energy dependence and enhancement in the ratios of other neutrino flavors from an AGN may provide an observational consequence for neutrino spin-flip in AGNs.

An interesting situation may arise after the incorporation of magnetic field twist effects, as discussed in case 4, which also give rise to change in the $\nu_e/\bar{\nu}_e$ ratio but for different (small) δm^2 values, irrespective of the nature of the VEP. The pure $\nu_e \rightarrow \bar{\nu}_e$ or $\bar{\nu}_e \rightarrow \nu_e$ (though suppressed [37]) may also take place giving rise to changes in the $\nu_e/\bar{\nu}_e$ ratio (for instance, different from unity), possibly with no energy dependence or change in the $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu)$ ratio. This can be realized from the discussion in case 4 of section III, where it is pointed out that an interplay between the VEP and a naturally scaled field twist leads to conversions in either the ν_e or $\bar{\nu}_e$ channel but not in both channels simultaneously. Note that in this case a nonzero Δf and a nonzero $\dot{\phi}$ is needed.

A relevant remark is that "matter like" effects induced by the presence of nonzero Δf (along with nonzero $\dot{\phi}$) differentiates between particles and antiparticles. Thus, if the measurement of the $\nu_e/\bar{\nu}_e$ ratio for high-energy neutrinos originating from AGNs were to become feasible, it may at least in principle constrain Δf to (much) smaller values than those which can currently be achieved by neutrinos from other astrophysical sources [4]. Let us note that a change in the $\nu_e/\bar{\nu}_e$ ratio is not expected from pure vacuum flavor oscillations. This can be a characteristic observational consequence of incorporating the effect of a possible (uniform) rotation of magnetic strength lines along the high-energy neutrino trajectories originating from AGNs.

The expected event rates for different neutrino flavors in a km^3 volume high-energy neutrino telescopes using the rather optimistic diffuse upper flux limits, as an example, given in Ref. [20] typically range, for $E \sim 10^6$ GeV, as follows: the downward going $(\nu_e + \bar{\nu}_e)$ event rate is typically $\sim O(10^{1.5})$, the downward going $(\nu_\mu + \bar{\nu}_\mu)$ event rate is typically $\sim O(10^2)$, whereas the downward going $(\nu_\tau + \bar{\nu}_\tau)$ event rate is typically $\sim O(10^1)$, all in units of per year per steradian, the downward going $\bar{\nu}_e$ event rate for $E \sim 6.4 \cdot 10^6$ GeV being approximately half an order of magnitude higher than the $(\nu_e + \bar{\nu}_e)$ event rate in the high-energy neutrino telescopes [38]. The three flavors are expected to have different event topologies [39], thus providing some prospects to search for the observational consequences pointed out in this section.

Summarizing, a possible observational consequence of neutrino spin-flip in the high-energy neutrino telescopes include a *change* in the expected $\nu_e/\bar{\nu}_e$ ratio correlated with the direction of the source with an energy resolution $\Delta E/E \gtrsim 1/20$ near the Glashow resonance energy as well as a possible energy dependence in the ratio of the three flavors. Some of the other situations in neutrino spin-flip discussed here tend to overlap with the pure vacuum flavor oscillations scenario.

V. Results and discussion

The intrinsic fluxes of the high-energy neutrinos ($E \geq 10^6$ GeV) originating from AGN are estimated to have the following ratios: $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu) \simeq 1/2$, $(\nu_\tau + \bar{\nu}_\tau)/(\nu_{e,\mu} + \bar{\nu}_{e,\mu}) \gtrsim 10^{-5}$. Thus, if an enhanced energy dependent $(\nu_\tau + \bar{\nu}_\tau)/(\nu_e + \bar{\nu}_e)$ ratio (as compared to no precession/conversion situation) is observed correlated to the direction of the source for high-energy neutrinos, then it may be either an evidence for a spin-flip through spin (flavor)-precession alone or, through a resonant conversion in the vicinity of the AGN due to an interplay

of VEP and/or a conceivable magnetic field twist in B_{AGN}, depending on the finer details of the relevant high-energy AGN neutrino spectra. The spin (flavor)-precession and/or conversion effects discussed in this paper may be distinguished from the pure vacuum flavor oscillations by observing the *energy dependence* of the high-energy neutrino flux profiles. A mutual comparison of the relevant [that is, for instance, $(\nu_e + \bar{\nu}_e)$ and $(\nu_\tau + \bar{\nu}_\tau)$] high-energy neutrino spectra may, in principle, help to isolate the mechanism of neutrino conversions in the vicinity of AGN.

The incorporation of a possible magnetic field twist induces a level crossing in the vicinity of AGN due to the VEP. This conversion can be made adiabatically resonant for a naturally scaled magnetic field twist with $\Delta f \gtrsim 10^{-34}$. A resonant character in the oscillations of high-energy neutrinos originating from AGN for vanishing gravity and vacuum mixings may not be induced otherwise. Thus a breakdown in the universality of gravitational coupling of neutrinos at the level of 10^{-34} or less, depending on the relevant δm^2 may provide a possible cause for observing energy dependence and change in the three neutrino flavors with respect to the pure vacuum flavor oscillations, assuming that there is no appreciable reverse neutrino spin-flip between the AGN and the earth.

For small δm^2 ($\delta m^2 < 5 \cdot 10^{-6}$ eV^2) a spin (flavor)-precession may result in an energy independent permutation of the relevant neutrino spectra with the corresponding spin (flavor)-precession probability greater than 1/2. This spin (flavor)-precession may occur for small Δf ($\Delta f \gtrsim 10^{-34}$). The spin-flip may occur through resonant conversions induced by the VEP and/or field twist in B_{AGN} as well. Assuming that the information on Δf 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 δm^2 ($\delta m^2 < 5 \cdot 10^{-6}$ eV^2), energy dependent permutations 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 twist in B_{AGN}.

For large δm^2 ($\delta m^2 > 5 \cdot 10^{-6}$ eV^2), if energy dependent distortions and, for instance, a change in $(\nu_\tau + \bar{\nu}_\tau)/(\nu_e + \bar{\nu}_e)$ is observed with the corresponding conversion probability greater than 1/2 then the cause may be a relatively large Δf ($\Delta f > 10^{-34}$) and/or a naturally scaled magnetic field twist. The level crossing induced by a VEP and/or field twist has a *different E* dependence, thus, in principle, with the improved information on either Δf or the scale of magnetic field twist, the cause of the conversion effect may be isolated. Further, as the energy span in the relevant high-energy AGN neutrino spectra is expected to be several orders of magnitude, therefore, energy dependent spin (flavor)-precession/conversion probabilities may result in distortions in some part(s) of the spectra for relevant neutrino species, and may thus be identifiable in future high-energy neutrino telescopes.

A possible observational consequence of neutrino spin-flip in AGNs in the electron neutrino channel only can be an observed *change* in the $\nu_e/\bar{\nu}_e$ ratio (as compared to no spin-flip situation) near the Glashow resonance energy, which may be a result of an interplay of the VEP and the magnetic field twist. This feature is absent in pure vacuum flavor oscillations.

An additional feature of the present study is that it may provide useful information on the strength/profile of B_{AGN} if the cause of $\nu_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ conversion/precession can be established due to the VEP and/or magnetic field twist for high-energy AGN neutrinos.

Acknowledgments

The authors thank World Laboratory (WL) for financial support within project E-13. HA also thanks Physics Division of National Center for Theoretical Sciences for financial support.

References

*E-mail: athar@phys.cts.nthu.edu.tw

[1] See, for instance, F. W. Stecker, C. Done, M. H. Salamon, and P. Sommers, Phys. Rev. Lett. **66**, 2697 (1991); **69**, 2738 (E) 1992. For a recent update, see, R. Gandhi, Nucl. Phys. (Proc. Suppl.) **B91**, 453 (2001).

[2] M. Gasperini, Phys. Rev. **D38**, 2635 (1988); **D39**, 3606 (1989).

[3] For an independent similar possibility of testing the VEP by neutrinos, see, A. Halprin and C. N. Leung, Phys. Rev. Lett. **67**, 1833 (1991).

[4] For a recent discussion in the context of atmospheric muon neutrino deficit, see, for instance, G. L. Fogli *et al.*, Phys. Rev. **D60**, 053006 (1999), and references cited therein, whereas for a recent discussion in the context of solar electron neutrino deficit, see, for instance, D. Majumdar, A. Raychaudhuri, and A. Sil, Phys. Rev. **D63**, 073014 (2001). For supernova neutrinos, see, M. M. Guzzo, H. Nunokawa, and R. Tomàs, hep-ph/0104054.

[5] C. Aneziris and J. Schechter, Int. J. Mod. Phys. **A6**, 2375 (1991); S. Toshev, Phys. Lett. **B271**, 179 (1991); C. Aneziris and J. Schechter, Phys. Rev. **D45**, 1053 (1992); E. Kh. Akhmedov, S. T. Petcov and A. Yu. Smirnov, Phys. Rev. **D48**, 2167 (1993); *ibid*, Phys. Lett. **B309**, 95 (1993).

[6] J. Vidal and J. Wudka, Phys. Lett. **B249**, 473 (1990); A. Yu. Smirnov, Phys. Lett. **B260**, 161 (1991); E. Kh. Akhmedov, P. I. Krastev and A. Yu. Smirnov, Z. Phys. **C52**, 701 (1991); T. Kubota *et al.*, Phys. Lett. **B292**, 195 (1992); M. Moretti, Phys. Lett. **B293**, 378 (1992); M. M. Guzzo and J. Bellandi, Phys. Lett. **B294**, 243 (1992); P. I. Krastev, Phys. Lett. **B303**, 75 (1993); A. B. Balantekin and F. Loreti, Phys. Rev. **D48**, 5496 (1993); M. M. Guzzo and J. Pulido, Phys. Lett. **B317**, 125 (1993); J. Bellandi and M. M. Guzzo, Phys. Lett. **B317**, 130 (1993); T. Kubota *et al.*, Phys. Rev. **D49**, 2462 (1994); K. Ohta and E. Takasugi, Prog. Theor. Phys. **92**, 733 (1994); V. M. Aquino, J. Bellandi and M. M. Guzzo, Physica Scripta **54**, 328 (1996); E. Kh. Akhmedov, hep-ph/9705451; J. Derkaoui and Y. Tayalati, Astropart. Phys. **14**, 351 (2001).

[7] H. Athar and J. T. Peltoniemi, Phys. Rev. **D51**, 5785 (1995); H. Athar, J. T. Peltoniemi and A. Yu. Smirnov, Phys. Rev. **D51**, 6647 (1995).

[8] K. Enqvist and V. Semikoz, Phys. Lett. **B312**, 310 (1993); V. Semikoz, Phys. Rev. **D48**, 5264 (1993); Erratum, *ibid*, **D49**, 6246 (1994); H. Athar, Phys. Lett. **B366**, 229 (1996).

[9] Sheldon L. Glashow, Phys. Rev. **118**, 316 (1960).

[10] J. G. Learned and S. Pakvasa, Astropart. Phys. **3**, 267 (1995).

[11] H. Athar and Guey-Lin Lin, hep-ph/0108204; *ibid*, hep-ph/0201026.

[12] See, for a recent discussion on various high-energy neutrino telescopes, L. Moscoso, Nucl. Phys.(Proc. Suppl.) **B87**, 377 (2000). See also, C. Spiering, Nucl. Phys. (Proc. Suppl.) **B91**, 445 (2001); F. Halzen, astro-ph/0111059.

[13] G. Domokos, S. Kovesi-Domokos, Phys. Lett. **B410**, 57 (1997); K. Enqvist, P. Keränen and J. Maalampi, Phys. Lett. **B438**, 295 (1998).

[14] M. Roy, J. Phys. **G22**, L113 (1996).

[15] Sarira Sahu and Vishnu M. Bannur, Mod. Phys. Lett. **A15**, 775 (2000).

[16] H. Athar and José F. Nieves, Phys. Rev. **D61**, 103001 (2000), and references cited therein.

[17] M. B. Voloshin, M. I. Vysotoskii and L. B. Okun, Sov. Phys. JETP **64**, 446 (1986).

[18] C. Lunardini and A. Yu. Smirnov, Nucl. Phys. **B583**, 260 (2000).

[19] See, for instance, Edward W. Kolb and Michael S. Turner, *The Early Universe* (Addison-Wesely Publishing Company, Reading, Massachusetts, 1990), pp. 244.

[20] A. P. Szabo and R. J. Protheroe, Astropart. Phys. **2**, 375 (1994).

[21] E. Kh. Akhmedov, S. T. Petcov and A. Yu. Smirnov, in Ref. [5].

[22] H. Minakata and A. Yu. Smirnov, Phys. Rev. **D54**, 3698 (1996).

[23] See, for instance, Ref. [16] for a brief description of high-energy tau neutrino production, whereas for a recent discussion on high-energy non tau neutrino production, see, Karl Mannheim, R. J. Protheroe and Jörg P. Rachen, Phys. Rev. **D63**, 023003 (2001), and references cited therein.

[24] For a recent update on AMANDA, see, E. Andres *et al.*, Nucl. Phys. (Proc. Suppl.) **B91**, 423 (2001).

[25] E. Waxman and J. N. Bahcall, Phys. Rev. **D59**, 023002 (1999); Phys. Rev. **D64**, 023002 (2001).

[26] M. Fukugita and S. Yazaki, Phys. Rev. **D36**, 3817 (1987); G. G. Raffelt, Astrophys. J. **365**, 559 (1990); V. Castellani and S. Degl'Innocenti, *ibid*, **402**, 574 (1993) [the present upper bound on neutrino magnetic moment from laboratory experiments is, $\mu < 1.5 \cdot 10^{-10} \mu_B$, see, D. E. Groom *et al.*, Euro. Phys. J. **C15**, 25 (2000)].

[27] M. C. Begelman, R. G. Blandford and M. Rees, Rev. Mod. Phys. **56**, 255 (1984).

[28] See, for instance, H. Sobel, Nucl. Phys. (Proc. Suppl.) **B91**, 127 (2001).

[29] For a recent discussion, see, H. Athar, M. Jeżabek and O. Yasuda, Phys. Rev. **D62**, 103007 (2000), and references cited therein; H. Athar, hep-ph/0008121.

[30] A. Yu. Smirnov, in Ref. [6].

[31] C.-S. Lim and W. J. Marciano, Phys. Rev. **D37**, 1368 (1988); E. Kh. Akhmedov, Sov. J. Nucl. Phys. **48**, 382 (1988) [Yad. Fiz. **48**, 599 (1988)]; Phys. Lett. **B213**, 64 (1988).

[32] See, for instance, C. W. Kim and A. Pevsner, *Neutrinos in Physics and Astrophysics* (Harwood academic publishers, 1993), p. 264.

[33] Thomas K. Gaisser, Francis Halzen and Todor Stanev, Phys. Rep. **258**, 173 (1995) and erratum **271**, 355 (1996).

[34] Karl Mannheim, J. Phys. **G27**, 1691 (2001).

[35] See, for instance, M. C. Gonzalez-Garcia, M. Maltoni, C. Pena-Garay and J. W. Valle, Phys. Rev. **D63**, 033005 (2001).

[36] H. Athar, Astropart. Phys. **14**, 217 (2000).

[37] E. Kh. Akhmedov, S. T. Petcov and A. Yu. Smirnov, in [5].

[38] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic, Astropart. Phys. **5**, 81 (1996); Phys. Rev. **D58**, 093009 (1998).

[39] H. Athar, G. Parente, and E. Zas, Phys. Rev. **D62**, 093010 (2000), and references cited therein.