Prospects for observations of high-energy cosmic tau neutrinos

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We study the prospects for the observation of high-energy cosmic tau neutrinos ($E \geqslant 10^6$ GeV) originating from proton acceleration in the cores of active galactic nuclei. We consider the possibility that vacuum flavor neutrino oscillations induce a tau to muon neutrino flux ratio greatly exceeding the rather small value expected from intrinsic production. The criteria and event rates for under water or ice light Čerenkov neutrino telescopes are given by considering the possible detection of downgoing high-energy cosmic tau neutrinos through characteristic double shower events.

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I. INTRODUCTION

Neutrino astronomy is now an emerging field and entails the need to have improved flux estimates as well as a good understanding of relevant detector capabilities for all flavor neutrinos, particularly in light of the recent growing experimental support for flavor oscillations [1]. Several high-energy cosmic neutrino ($>\sim 10^6$ GeV) detectors based on under water or ice muon detection are now at the proposal or construction stages [2] and alternative techniques for 10^9 GeV neutrinos are being considered through coherent radio [3] or acoustic [4] pulses as well as through horizontal air shower measurements with conventional arrays [5] or with fluorescent light either from the ground [6,7] or from orbiting detectors [8]. A number of astrophysical high-energy neutrino sources, such as active galactic nuclei (AGN), have been discussed in the literature and predicted to produce fluxes that could be detected in some of these detectors [9]. In the event of successful detection of high-energy astrophysical neutrinos the range of parameter space for flavor oscillations that can be tested could be considerably enhanced provided flavor identification can be done.

Cosmic tau neutrinos are possibly the easiest flavor to identify above 10^6 GeV. Two ideas have already been put forward based on the short decay lifetime of the τ produced in charged current interactions. There is a suggestion of measuring 10^6 GeV ν_τ flux through double shower (double bang) events in under water or ice Čerenkov telescopes [10]. A more recent suggestion is to detect a small pile up of upgoing μ-like events in the 10^4-10^5 GeV range with a fairly flat zenith angle dependence [11]. On the other hand the Landau-Pomeranchuk-Migdal (LPM) effect, that lengthens electromagnetic showers in water and ice, has been suggested to separate electron neutrino charged current interactions from the rest. This could be done with Čerenkov light detectors or with the radio technique for energies above 2×10^7 GeV [12]. It is conceivable that a combination of several of such techniques will allow the establishment of neutrino flavor ratios at energies above 10^6 GeV.

We will concentrate on cosmic tau neutrino detection in this article. Specifically, we discuss in some detail, the prospects for detection of high-energy cosmic tau neutrinos originating from the cores of AGN. We consider vacuum flavor oscillations as an example to illustrate the possibility offered by detectors in construction to distinguish between different neutrino flavors. For absolute event rates we use upper limit flux calculations as an example [13] and consider 1 km^2 detector sizes which are now being planned [2]. Both the energy ranges of interest and the relative numbers of τ- and μ-like event rates are, however, independent of the assumed normalization of the neutrino fluxes.

We show that for the chosen neutrino flux, a km^2 size surface area under ice or water Čerenkov light neutrino detector may be able to either set useful upper limits or may obtain first examples of the high-energy tau neutrinos originating from this cosmologically distant astrophysical source. The plan of the paper is as follows. In Sec. II, after a brief discussion of intrinsic production mechanisms of high-energy muon and tau neutrinos in AGNs, we estimate the relevant vacuum flavor oscillation probability. In Sec. III, we discuss in some detail the detection technique making use of the double shower structure of the tau neutrino charged current interactions and calculate the expected event rates for a typical km^2 surface size under water or ice detector. In Sec. IV, we summarize our results.

II. INTRINSIC COSMIC TAU NEUTRINO PRODUCTION AND VACUUM FLAVOR OSCILLATIONS

AGNs are the brightest objects in the sky and high-energy photons reaching tens of thousands of GeV have been observed from them. This is commonly interpreted as an indication that some kind of Fermi acceleration is taking place. In conventional models, electrons are the particles that get accelerated. It has been argued that if Fermi mechanisms are able to accelerate electrons in these objects, protons could also be accelerated by them. In proton acceleration models, the photons arise from neutral pion decays either in $p\gamma$ or pp collisions. If this is true, electron and muon neutrinos are also expected to be produced at similar flux levels from charged pion decays. Neutrino detection can provide the sig-

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nature for proton acceleration in AGN and it is one of the main goals of neutrino detectors in construction and design stages. For an update review of various ν_e and ν_μ flux estimates from AGNs in $p\gamma$ and pp collisions (as well as from some other interesting astrophysical or cosmological sites), see [14]. We will here explore the expected tau neutrino fluxes intrinsically produced in the collisions and how these fluxes can vary in a possible neutrino oscillation scenario.

In $p\gamma$ collisions, high-energy ν_e and ν_μ are mainly produced through the resonant reaction $p+\gamma\to\Delta^+\to n+\pi^+$. The same collisions will give rise to a greatly suppressed high-energy ν_τ (and $\overline{\nu_\tau}$) flux mainly through the reaction $p+\gamma\to D_S^+ +\Lambda^0+\overline{D}^0$. The production cross section for D_S^+ is essentially up to three orders of magnitude lower than that of Δ^+ production for the relevant center of mass energy scale. Moreover the branching ratio of $D_S^\pm$ to decay eventually into ν_τ ($\overline{\nu_\tau}$) is approximately two orders of magnitude lower than for Δ^+ to subsequently decay into ν_e and ν_μ through π^+. These two suppression factors along with the relevant kinematic limits give approximately the ratio of intrinsic fluxes of tau neutrinos and muon neutrinos as $(\nu_\tau+\overline{\nu_\tau})/(\nu_\mu+\overline{\nu_\mu})<10^{-5}$.

In pp collisions, the ν_τ flux may be obtained through $p+p\to D_S^+ +X$. The relatively small cross section for D_S^+ production together with the low branching ratio into ν_τ implies that the ν_τ flux in pp collisions is also suppressed up to $4-5$ orders of magnitude relative to ν_e and/or ν_μ fluxes. The situation is quite similar to the prompt atmospheric ν_τ flux calculation; the result is basically a rescaling of the prompt ν_μ flux from the decay of charmed D's and results in a negligibly small ν_τ flux for the energies under discussion [15,16].

In proton acceleration models the intrinsically produced tau neutrino flux is thus expected to be very small, typically a factor between 10^{-5} and 10^{-6} relative to electron and muon neutrino fluxes [17]. However, recent experimental measurements of atmospheric neutrinos suggest that neutrinos could just have vacuum flavor oscillations and the tau neutrino flux would be dramatically enhanced.

It has been pointed out that there are no matter effects for high-energy cosmic tau neutrinos originating from cores of AGNs primarily because of relatively small matter density in the vicinity of core of the AGN for all relevant δm^2 [18]. We will restrict the following discussion to vacuum oscillations between two flavors, ν_μ and ν_τ, for simplicity.

The flavor precession probability for nonvanishing vacuum mixing angle is obtained from the effective Hamiltonian matrix in the two flavor basis $\psi^T=(\nu_\mu,\nu_\tau)$:

$$\begin{pmatrix} 0 & \frac{\delta}{2}\sin 2\theta \\ \frac{\delta}{2}\sin 2\theta & \delta\cos 2\theta \end{pmatrix}, \qquad (1)$$

where $\delta=\delta m^2/2E$ with $\delta m^2=m^2(\nu_\tau)-m^2(\nu_\mu)$ and E the neutrino energy, leading to the well-known result

$$P(\nu_\mu\to\nu_\tau)=\sin^2 2\theta\sin^2\left(\frac{\delta m^2}{4E}L\right). \qquad (2)$$

If we take the values of $\sin^2 2\theta$ and δm^2 suggested by recent SuperKamiokande data ($\sin^2 2\theta\sim 1$, $\delta m^2\sim 10^{-3}$ eV^2) [19] and $L\sim 100$ Mpc (1 pc$\simeq 3\times 10^{16}$ m) as a representative distance between the AGN and our galaxy, then the above rapidly oscillating probability averages out to $\sim 1/2$ for all relevant neutrino energies to be considered for detection. Very similar fluxes of muon and tau neutrinos would thus be expected. Let us further note that after averaging the P given by Eq. (2) is independent of not only E but also δm^2 and thus leads to a constant suppression of high-energy cosmic muon neutrino flux.

The deficit measured by superkamiokande in atmospheric muon neutrino flux may currently be explained either through $\nu_\mu\to\nu_\tau$ or through $\nu_\mu\to\nu_s$, where ν_s is a sterile neutrino.[1] In the first case and for high-energy neutrinos originating at cosmological distances, the ratio $(\nu_\tau+\overline{\nu_\tau})/(\nu_\mu+\overline{\nu_\mu})$ is close to 1/2. Therefore, a ratio different from 1/2 excludes this possibility.

III. DETECTION OF HIGH-ENERGY COSMIC TAU NEUTRINOS

High-energy cosmic tau neutrino detection could be achieved by making use of the characteristic double shower events [10] or by the pileup effect expected as they travel through the Earth [11]. Such events could be seen in conventional neutrino telescopes and in principle also with other alternative techniques that have been proposed. We will discuss in some detail the possibility of detecting double shower events for conventional underground telescopes by estimating rates using the the fluxes of Ref. [13] and the oscillation probability addressed in the previous section. This is intended to provide a reference calculation.

The downgoing cosmic tau neutrinos reaching close to the surface of the detector may undergo a charged current deep inelastic scattering with nuclei inside or 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 decaying 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 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* μ-like track [10].

We are going to restrict our estimate to down going neutrinos as at these energies tau neutrinos that go through the Earth interact. Effectively the process of interaction and tau decays can be regarded as an energy degradation to the range 10^4–10^5 GeV [11]. Unfortunately the two shower signature

[1] Although, $\nu_\mu\to\nu_s$ is now being disfavored [20].

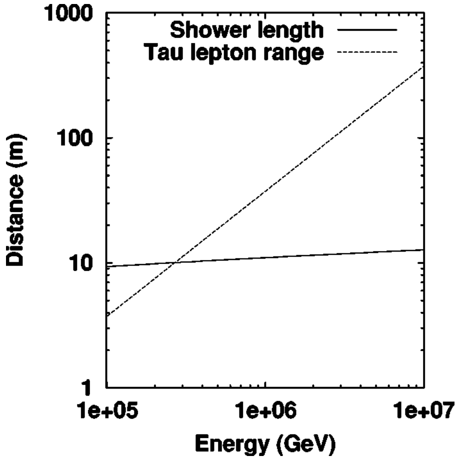

FIG. 1. Comparison of the tau lepton range and the shower length of the first shower (defined as twice the depth at maximum) for ice or water.

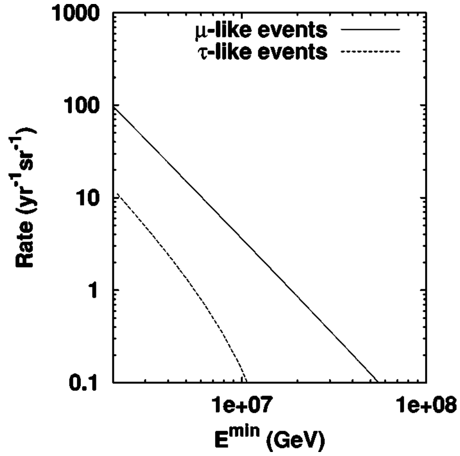

FIG. 2. Expected downgoing μ-like and τ-like event rate produced by AGN neutrinos from Ref. [13] because of vacuum flavor oscillations as a function of the minimum energy of the corresponding lepton.

will be difficult to be resolved below $\sim 3\times 10^5$ GeV (see below).

For downgoing cosmic tau neutrinos, the *double bang* event rate in water or ice is estimated using [21]

$$\text{Rate} = A\int \mathrm{d}E P_\tau(E,E_\tau^{\min})\,\frac{dN}{dE}, \tag{3}$$

where A is the area of the neutrino telescope and P_τ gives the probability that a tau neutrino of energy E produces two contained and separable showers with the tau lepton energy greater than $E_\tau^{\min}$. It is given by

$$P_\tau(E,E_\tau^{\min}) = \rho_{\mathrm{m}} N_A \int_0^{1-E_\tau^{\min}/E} dy[D-R_\tau]\frac{d\sigma^{CC}(E,y)}{dy}, \tag{4}$$

where N_A is the Avogadro's number, ρ_{m} is the density of the detector medium, $d\sigma^{\mathrm{CC}}/dy$ is the charged current $\nu_\tau N$ differential cross section, y is the fraction of neutrino energy that is transferred to the hadron in the laboratory frame. D is the detector length scale which we fix to be 1 km and the tau lepton range R_τ which must be contained within D is given by

$$R_\tau = \frac{E(1-y)\tau c}{m_\tau c^2}. \tag{5}$$

In Eq. (5), τc is the lifetime and $m_\tau c^2$ is the mass of the high-energy tau lepton.

The lower limit of integration in Eq. (3) is $E_\tau^{\min}$. We take $E_\tau^{\min}$ greater than $\sim 2\times 10^6$ GeV because at this energy the tau lepton range (separation between the two showers) in water is $\sim$100 m which allows a clear separation between the two showers. The upper limit of integration in Eq. (3) is taken to be $E \lesssim 2\times 10^7$ GeV as for energies above it the tau lepton range exceeds the telescope size (see Fig. 1).

Finally in Eq. (3), dN/dE is the differential high-energy tau neutrino flux and is obtained by multiplying $P(\nu_\mu \to \nu_\tau)$ given by Eq. (2) with dN/dE for $(\nu_\mu + \overline{\nu_\mu})$ taken from Ref. [13]. In Fig. 2, we depict downgoing differential event rates for double shower events using the parton distributions Martin-Roberts-Stirling set R_1 (MRS R_1) from [22] for km^2 under water neutrino telescopes as an example. We have checked that other modern parton distributions give quite similar events rates and are therefore not depicted here. We have taken into account the fact that $\sim$15% of the times the tau decay does not induce any shower. For comparison we also plot the μ-like event rate induced by muon neutrinos. Note that these 15% and the tau neutrino interactions in which the tau lepton decays outside the detector volume have identical (μ-like) experimental signature.

The signature of double shower events depends on the detector capabilities for shower identification and energy resolution and difficulties can be envisaged. We have used 100 m as the minimum distance to resolve two showers, what is quite conservative in view of typical spacing between optical modules in an under water or ice detector. In Fig. 3, we show the dependence of shower size and shower separation on neutrino energy E in ice and in water for which we have used the parametrization of Ref. [23]. As shower size is basically proportional to energy, the size of the second shower is on average a factor of 2 higher than the first one (see also Ref. [10]). This value results by taking into account the relevant kinematics of the allowed decay channels and the corresponding branching ratios and using the average energy transfer $\langle y\rangle = 0.25$. The y distribution and decay kinematics will lead to a spread in this ratio. While $y=0.1$ enhances the energy ratio of the second and first showers to a value of about 6, for y values higher than 0.4 the ratio of the two shower sizes starts to be lower than unity obscuring the tau neutrino signature.

Another relevant point is the evaluation of the backgrounds, a double shower signature not induced by a tau neutrino. As was discussed in Ref. [10] such a probability is very small and should not affect the detection of the high-energy cosmic tau neutrino. Also one should take into ac-

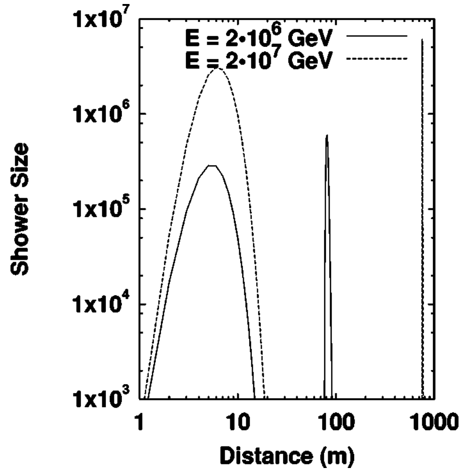

FIG. 3. Typical longitudinal development of a double shower produced by the deep inelastic charged current interaction of the high-energy cosmic tau neutrino.

count the possibility that the muon component of a single cascade induced from a muon or an electron neutrino charged/neutral current interaction can be confused with the second shower of the tau lepton decay. However, in this case the size of the second shower is smaller than the first one which should be sufficient to distinguish it from a tau neutrino event. Thus, the selection criteria of amplitude of second shower greater than the first one typically by a factor of ~ 2, depending on y value, essentially makes the observation background free.

The high-energy neutrino telescopes have quite small double shower event rates ($\mathrm{yr}^{-1}\,\mathrm{sr}^{-1}$) due to small high-energy intrinsic tau neutrinos flux, thus any observed change in this situation may provide indirect evidence of neutrino mass. A corresponding comparable change in this situation is currently not expected from variations of astrophysical model inputs. The almost simultaneous measurement of the two showers may provide useful information on the incident neutrino energy as well as the y distribution.

Summarizing, in the context of relevant backgrounds, we envisage essentially the simultaneous presence of two types of events (with different topologies) serving as background for the tau neutrino induced contained but separable double showers connected by a μ-like track such that the amplitude of the second shower is typically 2 times the first one. The first type of background events are due to relatively long (~ 10 km) range muons passing through the detector identified as μ-like tracks. Their estimated number is given by the upper slanted curve in Fig. 2. The second type of background is the single showers due to charged/neutral current interactions. These may be estimated as 1/10 of the continuous μ-like tracks. Thus, the signature of the tau neutrinos as emphasized earlier remained distinct from these two type of backgrounds.

We emphasize that within the respective energy window, the essential factor in prospective detection of contained but separable double shower events connected by a μ-like track as a signature of tau neutrinos is the *difference* in the incident tau neutrino energy dependences on spread and separation of the two showers. This *difference* is also clearly crucial for separating the tau neutrino events from the (relatively abundent) μ-like events.

IV. RESULTS

The intrinsic fluxes of the high-energy cosmic neutrinos originating from proton acceleration in cores of AGNs are estimated to have typically the following ratios: $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu) < 10^{-5}$. Thus, if an enhanced $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu)$ ratio (as compared to no precession situation) is observed *correlated* to the direction of source for high-energy cosmic neutrinos, then it may be an evidence for vacuum flavor oscillations of neutrinos induced by nonzero vacuum mixing angle depending on the finer details of the relevant high-energy cosmic neutrino spectra. For vacuum flavor oscillations of high-energy cosmic neutrinos, the relevant range of neutrino mixing parameters are $\delta m^2 \sim 10^{-3}$ eV^2 with $\sin^2 2\theta \sim 1$.

We have identified the incident tau neutrino energy range and the relevant neutrino mixing parameters which may give rise to high-energy cosmic tau neutrino induced downward contained but separable double shower events. For $2\times 10^6 \lesssim E/\mathrm{GeV} \lesssim 2\times 10^7$, a km^2 detector may be able to obtain first examples of downgoing high-energy cosmic tau neutrinos through contained but separable double shower events or may at least provide some useful relevant upper limits.

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[1] G. Raffelt, in Proceedings of 1998 Summer School in High-Energy Physics and Cosmology, edited by G. Senjanovic and A. Yu. Smirnov, ICTP, Trieste, Italy, 1998, hep-ph/9902271, and references cited therein.

[2] See, for instance, L. Moscoso, in Sixth International Workshop on Topics in Astroparticle and Underground Physics (TAUP 99), Paris (France), 1999, edited by M. Froissart, J. Dumarchez, and D. Vignaud, Report No. DAPNIA-SPP-00-01, 2000.

[3] See, for a latest discussion, J. Alvarez-Muñiz and E. Zas, Phys. Lett. B **434**, 396 (1998).

[4] L.G. Dedenko *et al.*, in Proceedings of 25th International Cosmic Ray Conference, edited by M.S. Potgieter, B.C. Raubenheimer, and D.J. Van Der Walt, Durban, South Africa, Vol. 7, p. 89.

[5] K.S. Capelle, J.W. Cronin, G. Parente, and E. Zas, Astropart.

Phys. **8**, 321 (1998).
[6] S.C. Corbato *et al.*, Nucl. Phys. B (Proc. Suppl.) **28**, 36 (1992).
[7] Telescope Array Collaboration, N. Hayashida *et al.*, astro-ph/9804043.
[8] See, for instance, G. Domokos and S. Kovesi-Domokos, hep-ph/9801362; hep-ph/9805221. See also, D. Fargion, astro-ph/0002453, and references cited therein.
[9] Thomas K. Gaisser, Francis Halzen, and Todor Stanev, Phys. Rep. **258**, 173 (1995); **271**, 355(E) (1996).
[10] J.G. Learned and S. Pakvasa, Astropart. Phys. **3**, 267 (1995).
[11] F. Halzen and D. Saltzberg, Phys. Rev. Lett. **81**, 4305 (1998). For some recent discussions, see, S.I. Dutta, M.H. Reno, and I. Sarcevic, hep-ph/0005310; J. Alvarez-Muñiz, F. Halzen, and D.W. Hooper, Phys. Rev. D (to be published), astro-ph/0006027.
[12] J. Alvarez-Muñiz, R.A. Vázquez, and E. Zas, Phys. Rev. D **61**, 023001 (2000).
[13] A.P. Szabo and R.J. Protheroe, Astropart. Phys. **2**, 375 (1994).
[14] See, for instance, R.J. Protheroe, Nucl. Phys. B (Proc. Suppl.) **77**, 465 (1999), and references cited therein.
[15] F. Halzen, B. Keszthelyi, and E. Zas, Phys. Rev. D **52**, 3239 (1995); L. Pasquali and M.H. Reno, *ibid.* **59**, 093003 (1999).
[16] M.C. Gonzalez-Garcia and J.J. Gomez-Cadenas, Phys. Rev. D **55**, 1297 (1997).
[17] A more detailed numerical study supports this estimate; H. Athar, R. A. Vázquez, and E. Zas (in preparation).
[18] See, for example, H. Athar, M. Jeżabek, and O. Yasuda, hep-ph/0005104, and references cited therein.
[19] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998); Phys. Lett. B **433**, 9 (1998); **436**, 33 (1998); **467**, 185 (1999).
[20] M. Nakahata, talk given at Sixth International Workshop on Topics in Astroparticle and Underground Physics (TAUP 99), Paris, France, edited by M. Froissart, J. Dumarchez, and D. Vignaud.
[21] R. Gandhi, C. Quigg, M.H. Reno, and I. Sarcevic, Astropart. Phys. **5**, 81 (1996); Phys. Rev. D **58**, 093009 (1998).
[22] A.D. Martins, R.G. Roberts, and W.J. Stirling, Phys. Lett. B **387**, 419 (1996).
[23] T.K. Gaisser, *Cosmic Rays and Particle Physics* (Cambridge University Press, Cambridge, England, 1990), and references cited therein.