PHYSICAL REVIEW D **71,** 103008 (2005)

Tau neutrino astronomy in GeV energies

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(Received 20 July 2004; published 24 May 2005)

We point out the opportunity of the tau neutrino astronomy for the neutrino energy E ranging between 10 GeV and 10^3 GeV. In this energy range, the intrinsic tau neutrino production is suppressed relative to the intrinsic muon neutrino production. Any sizable tau neutrino flux may thus arise because of the $\nu_\mu \to \nu_\tau$ neutrino oscillations only. It is demonstrated that, in the presence of the neutrino oscillations, consideration of the neutrino flavor dependence in the background atmospheric neutrino flux leads to the drastically different prospects between the observation of the astrophysical muon neutrinos and that of the astrophysical tau neutrinos. Taking the galactic-plane neutrino flux as the targeted astrophysical source, we have found that the galactic-plane tau neutrino flux dominates over the atmospheric tau neutrino flux for $E \gtrsim 10$ GeV. Hence, the galactic-plane can at least in principle be seen through the tau neutrinos with energies just greater than 10 GeV. In a sharp contrast, the galactic-plane muon neutrino flux is overwhelmed by its atmospheric background until $E \gtrsim 10^6$ GeV.

DOI: 10.1103/PhysRevD.71.103008 PACS numbers: 95.85.Ry, 14.60.Pq, 96.40.Tv, 98.38.−j

I. INTRODUCTION

The $\nu_\mu \to \nu_\tau$ neutrino oscillations established by the high-statistics Super-Kamiokande (SK) detector, ensure that a non-negligible ν_τ flux reaches the Earth. A recent SK analysis of the atmospheric neutrino data implies the following range of the neutrino mixing parameters [1]

$$\delta m^2 = (1.9 - 3.0) \cdot 10^{-3}\ \mathrm{eV}^2, \quad \sin^2 2\theta > 0.9. \tag{1}$$

This is a 90%C.L. range of the neutrino mixing parameters with the best-fit values given by $\delta m^2 = 2.4 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$, respectively.

The tau neutrinos resulting from the above $\nu_\mu \to \nu_\tau$ oscillations are presently identified on the statistical basis [2]. On the other hand, the total number of observed nontau neutrinos from various detectors are already greater than $\sim 10^4$ with energies ranging from $\sim 10^{-1}$ GeV to $\sim 10^3$ GeV [3]. It is essential to develop efficient techniques to identify the tau neutrinos [4].

There are at least two important reasons for observing the ν_τ. First, seeing the ν_τ confirms the $\nu_\mu \to \nu_\tau$ oscillation interpretation for the atmospheric neutrino data. Second, since the atmospheric ν_τ flux is generally suppressed as compared to the atmospheric ν_μ flux, the prospective observation of the astrophysical ν_τ suffers *much less* background than in the ν_μ case.

In this paper, we address the second point with the galactic-plane tau neutrinos as our illustrating astrophysical source. We point out that *contrary* to the general expectations, the atmospheric neutrino flux *does not* dominate over the astrophysical neutrino flux for the neutrino energy $E < 10^3$ GeV, once the flavor composition of the neutrino flux is taken into account. The idea for such an investigation has appeared earlier in Ref. [5].

In the context of two neutrino flavors, ν_μ and ν_τ, the total tau neutrino flux arriving at the detector on Earth, after traversing a distance L, is

$$\phi^{\mathrm{tot}}_{\nu_\tau}(E) = P(E) \cdot \phi_{\nu_\mu}(E) + (1 - P(E)) \cdot \phi_{\nu_\tau}(E), \tag{2}$$

where $P(E) \equiv P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \cdot \sin^2(L/L_{\mathrm{osc}})$ with the neutrino oscillation length given by $L_{\mathrm{osc}} = 4E/\delta m^2$.

In order to compute the total ν_τ flux from a given astrophysical site, we need to first compute the intrinsic ν_μ as well as the intrinsic ν_τ flux from the same site.

II. GALACTIC-PLANE NEUTRINO FLUX

One calculates the intrinsic galactic-plane ν_μ and ν_τ fluxes by considering the collisions of incident cosmic-ray protons with the interstellar medium. The fluxes are given by

$$\phi_\nu(E) = R n_p \int_E^\infty \mathrm{d}E_p \phi_p(E_p) \frac{\mathrm{d}\sigma_{pp\to\nu+Y}}{\mathrm{d}E}, \tag{3}$$

where E_p is the energy of the incident cosmic-ray proton, $\mathrm{d}\sigma_{pp\to\nu+Y}/\mathrm{d}E$ is the ν energy spectrum in the pp collisions. R is the typical distance in the galaxy along the galactic-plane, which we take as 10 kpc(1 pc $\sim 3 \cdot 10^{13}$ km). The density of the interstellar medium n_p along the galactic plane is taken to be $\sim$1 proton per cm^3. The primary cosmic-ray proton flux, $\phi_p(E_p) \equiv \mathrm{d}N_p/\mathrm{d}E_p$, is given by [6]

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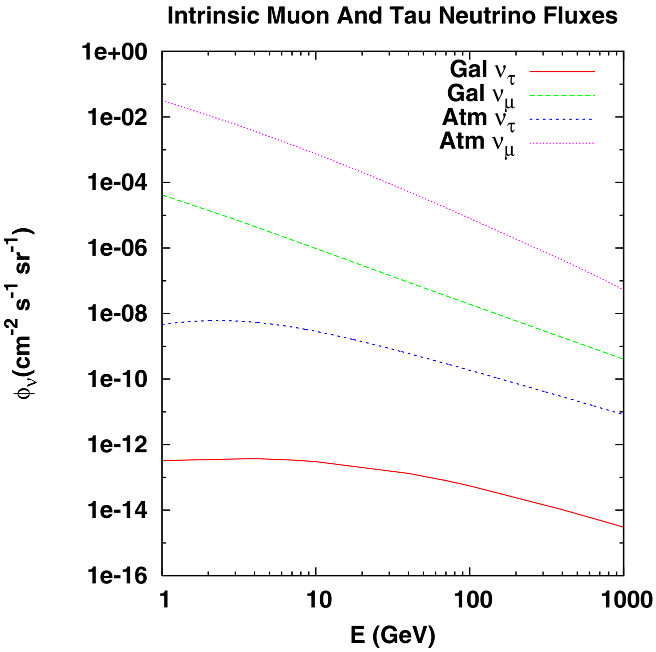

FIG. 1 (color online). The intrinsic galactic-plane and the intrinsic downward going atmospheric muon and tau neutrino fluxes as a function of the neutrino energy in GeV. Details are provided in the text.

$$\phi_p(E_p) = 1.49 \cdot (E_p + 2.15 \cdot \exp(-0.21\sqrt{E_p}))^{-2.74}, \quad (4)$$

in units of cm^{-2} s^{-1} sr^{-1} GeV^{-1}. The above flux is under the assumption that the cosmic-ray flux spectrum in the galaxy is a constant and equal to its locally observed value. The galactic-plane neutrino flux (abbreviated here as Gal) is sometimes also referred to as the galactic center region neutrino flux (abbreviated as G or GC), the galactic disk neutrino flux or the Milky Way neutrino flux. We shall estimate here the neutrino flux coming from the galactic-plane direction only as transverse to it, the n_p decreases essentially exponentially [7], and so does the $\phi_\nu(E)$ according to Eq. (3).

The neutrino production process $p + p \to \nu + Y$ is mediated by the production and the decays of the π, the K, and the charmed hadrons. The galactic muon neutrinos mainly come from the two-body π decays and the subsequent three-body muon decays. While the decay rates and the decay distributions of the π and the μ are well understood, the differential cross section for the process $p + p \to \pi + Y$ is model dependent. We adopt the parametrization for this cross section from Ref. [8], which is obtained by using the accelerator data in the sub-TeV energy range [9]. We remark that our galactic-plane ν_μ flux compares well with a previous calculation [7] using the PYTHIA [10].

The galactic-plane ν_τ flux arises from the production and the decays of the D_s mesons. It has been found to be rather suppressed compared to the corresponding ν_μ flux [11]. Figure 1 shows the intrinsic galactic-plane ν_μ and ν_τ fluxes obtained by using the above description (along with the corresponding intrinsic downward going atmospheric neutrino fluxes). We shall use these in our subsequent estimates.

The total galactic-plane tau neutrino flux, $\phi^{\rm tot}_{\nu_\tau}(E)$, is therefore *dominated* by the $\nu_\mu \to \nu_\tau$ oscillations indicated by the term $P(E) \cdot \phi_{\nu_\mu}(E)$ in Eq. (2). With the best-fit values for the neutrino mixing parameters, we have $\phi^{\rm tot}_{\nu_\tau}(E) \approx \phi_{\nu_\mu}(E)/2$, neglecting the contribution of $\phi_{\nu_\tau}(E)$, since $L_{\rm osc} \ll L$, where $L \sim 5$ kpc. The *total* galactic-plane tau neutrino flux, $\phi^{\rm tot}_{\nu_\tau}(E) \equiv {\rm d}N/{\rm d}(\log_{10}E)$, can be parameterized for 1 GeV $\leq E \leq 10^3$ GeV, as

$$\phi^{\rm tot}_{\nu_\tau}(E) = A\left(\frac{E}{\rm GeV}\right)^{\alpha}, \quad (5)$$

where $A = 2 \cdot 10^{-5}$ is in units of cm^{-2} s^{-1} sr^{-1} with $\alpha = -1.64$.

III. ATMOSPHERIC NEUTRINO FLUX

The calculation of the total atmospheric tau neutrino flux is more involved. We follow the approach in Ref. [8] for computing the intrinsic atmospheric ν_μ flux which can oscillate into ν_τ.

For the π-decay contribution, the flux formula reads:

$$\frac{{\rm d}^2N^\pi_{\nu_\mu}(E,\xi,X)}{{\rm d}E{\rm d}X} = \int_E^\infty {\rm d}E_N \int_E^{E_N} {\rm d}E_\pi \frac{\Theta(E_\pi - \frac{E}{1-\gamma_\pi})}{d_\pi E_\pi(1-\gamma_\pi)} \times \int_0^X \frac{{\rm d}X'}{\lambda_N} P_\pi(E_\pi, X, X') \times \frac{1}{E_\pi} F_{N\pi}(E_\pi, E_N) \times \exp\left(-\frac{X'}{\Lambda_N}\right)\phi_N(E_N), \quad (6)$$

where E is the neutrino energy and ξ is the zenith angle in the direction of the incident cosmic-ray nucleons. The $\gamma_\pi = m^2_\mu/m^2_\pi$ and d_π is the pion decay length in units of g/cm^2. The λ_N is the nucleon interaction length while Λ_N is the corresponding nucleon attenuation length. $\phi_N(E_N)$ is the primary cosmic-ray flux spectrum. We only consider the proton component of ϕ_N, which is given by Eq. (4). We take $\lambda_N = 86$ g/cm^2 and $\Lambda_N = 120$ g/cm^2 [9]. The function $P_\pi(E_\pi, X, X')$ is the probability that a charged pion produced at the slant depth X' (g/cm^2) survives to the slant depth $X(>X')$. The $F_{N\pi}(E_\pi, E_N)$ is the normalized inclusive cross section for $N + {\rm air} \to \pi^\pm + Y$, and is given in the Ref. [8].

The kaon contribution to the atmospheric ν_μ flux has the same form as Eq. (6) with an inclusion of the branching ratio $B(K \to \mu\nu) = 0.635$ and appropriate replacements in the kinematics factors as well as in the normalized inclusive cross section. We remark that the current ap-

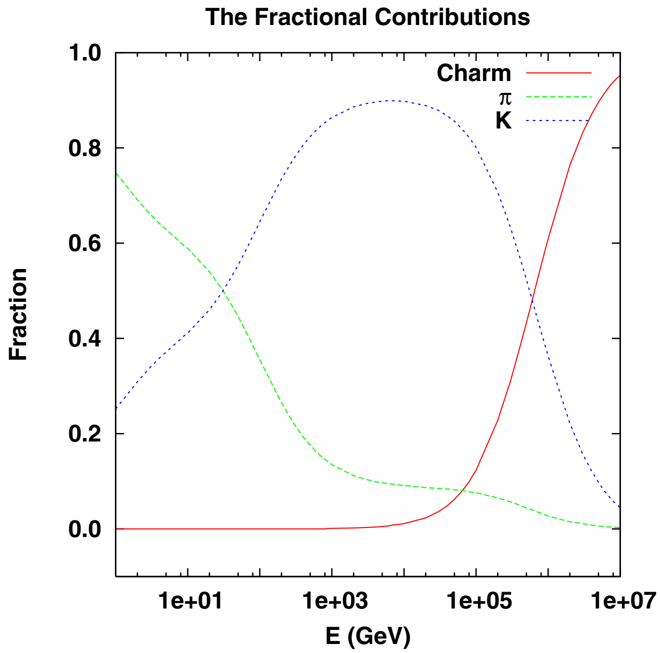

FIG. 2 (color online). The fraction of contributions by the π, the K, and the charm decays to the overall downward going atmospheric ν_μ flux as a function of the neutrino energy in GeV.

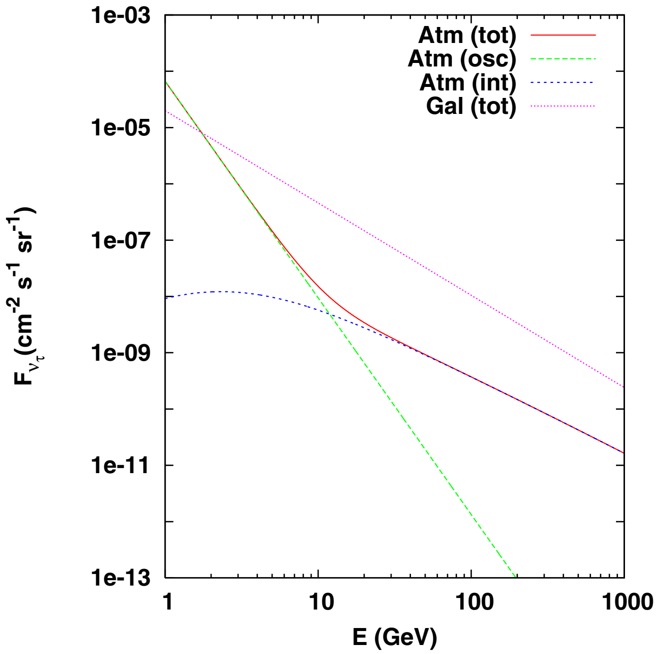

FIG. 3 (color online). Comparison of the total galactic-plane tau neutrino flux with the total downward going atmospheric neutrino flux for the best-fit values of the neutrino mixing parameters as a function of the neutrino energy. The intrinsic and oscillated parts of the total downward going atmospheric tau neutrino flux are also shown as a function of the neutrino energy in GeV.

proach neglects the 3-body muon-decay contribution to the ν_μ flux. This is a good approximation for $E > 10$ GeV [8]. The relevance of the muon-decay contribution for $1 \text{ GeV} \leq E \leq 10$ GeV will be commented later.

We stress that the π and the K decays are not the only sources for the atmospheric ν_μ flux. For $E > 10^6$ GeV, the charm-decay contribution becomes more important than those of the π and the K decays. We have used the results from the perturbative QCD to estimate this contribution [12]. The muon neutrino flux due to charm contribution can be written as

$$\frac{\mathrm{d}^2 N^c_{\nu_\mu}(E, X)}{\mathrm{d}E\mathrm{d}X} = \sum_h \frac{Z_{ph} Z_{h\nu_\mu}}{1 - Z_{pp}(E)} \cdot \frac{\exp(-X/\Lambda_p)\phi_p(E)}{\Lambda_p}, \tag{7}$$

where h stands for the $D^\pm$, the D^0, the D_s and the Λ_c hadrons. The Z moments on the RHS of the equation are defined by

$$Z_{ij}(E_j) \equiv \int_{E_j}^{\infty} \mathrm{d}E_i \frac{\phi_i(E_i)}{\phi_i(E_j)} \frac{\lambda_i(E_j)}{\lambda_i(E_i)} \frac{\mathrm{d}n_{iA\to jY}(E_i, E_j)}{\mathrm{d}E_j}, \tag{8}$$

with $\mathrm{d}n_{iA\to jY}(E_i, E_j) \equiv \mathrm{d}\sigma_{iA\to jY}(E_i, E_j)/\sigma_{iA}(E_i)$. In the decay process, the scattering length λ_i is replaced by the decay length d_i, whereas the $\mathrm{d}n_{iA\to jY}(E_i, E_j)$ is replaced by the $\mathrm{d}\Gamma_{i\to jY}(E_i, E_j)/\Gamma_i(E_i)$. We note that this part of the atmospheric ν_μ flux is isotropic, unlike the contributions from the π and the K decays. This difference is attributable to the lifetime difference between the charm and the $\pi(K)$ mesons. The various Z moments are calculated using the next-to-leading order perturbative QCD [13,14]. The decay moments $Z_{h\nu_\mu}$ are calculated by using the charmed-hadron decay distributions given in Refs. [15,16].

We show the relative contributions by the π, the K, and the charm decays to the overall ν_μ flux in Fig. 2. This is an extension of the Fig. 3 in Ref. [8], where only the π and the K contributions are compared. It is obvious that the π decay contribution dominates for $1 \text{ GeV} \leq E \leq 10$ GeV, while the K decay contribution dominates between 10^3 GeV and 10^5 GeV. The fraction of the charm-decay contribution rises rapidly at $E \geq 10^5$ GeV and becomes dominant for $E > 10^6$ GeV. In this energy range, both the π and the K lose large fractions of their energies before decaying into the neutrinos.

Additionally, the intrinsic atmospheric ν_τ flux is also required to completely determine the total atmospheric ν_τ flux. This flux is calculated using the perturbative QCD, since τ neutrino arises from the D_s decays [17]. The flux is written as Eq. (7) with Z_{ph} replaced by the Z_{pD_s} and $Z_{h\nu_\tau}$ replaced by the $Z_{D_s\nu_\tau}$. We note that the $Z_{D_s\nu_\tau}$ contains two contributions. One arises from the decay $D_s \to \nu_\tau \tau$; the other follows from the subsequent tau-lepton decay, $\tau \to \nu_\tau + Y$. The latter contribution is calculated using the decay distributions of the decay modes $\tau \to \nu_\tau \rho$,

$\tau \to \nu_\tau \pi$, $\tau \to \nu_\tau a_1$ [17,18], and the $\tau \to \nu_\tau l \nu_l$ [9,16] (Fig. 1 shows the intrinsic downward going atmospheric muon and tau neutrino fluxes for $1\ \mathrm{GeV} \leq E \leq 10^3\ \mathrm{GeV}$).

We have calculated the $\phi^{\mathrm{tot}}_{\nu_\tau}(E)$ by applying Eq. (2) with $\phi_{\nu_{\mu,\tau}}(E)$ given by $\mathrm{d}^2 N_{\nu_{\mu,\tau}}(E, X)/\mathrm{d}E\mathrm{d}X$ and integrating over the slant depth X. For $\xi < 70°$, the oscillation probability $P(\nu_\mu \to \nu_\tau)$ is calculated using the relation $X = X_0 \exp(-L\cos\xi/h_0)/\cos\xi$ with $X_0 = 1030\ \mathrm{g/cm^2}$ and $h_0 = 6.4$ km. Here L is the linear distance from the neutrino production point to the detector on the Earth [19]. This gives, for instance, $P(\nu_\mu \to \nu_\tau) \simeq \sin^2(4.5 \cdot 10^{-2}(\mathrm{GeV}/E))$ at $\xi = 0°$, for the best-fit values of the neutrino mixing parameters.

IV. THE COMPARISON

The comparison of the galactic-plane and the downward going atmospheric ν_τ flux is given in Fig. 3 and 4 in the presence of neutrino oscillations (we plot $\mathrm{d}N_\nu/\mathrm{d}(\log_{10} E)$ instead of $\mathrm{d}N_\nu/\mathrm{d}E$). The former flux clearly *dominates* the latter for $E \gtrsim 10$ GeV, whereas the two fluxes cross at $E = 2.3$ GeV for $\delta m^2 = 2.4 \cdot 10^{-3}\ \mathrm{eV}^2$ and $\sin^2 2\theta = 1$. This comparison is however subject to the uncertainty of galactic-plane ν_τ flux by the choices of the density n_p and the distance R mentioned before.

One can see that the atmospheric ν_τ flux is sensitive to the value of δm^2 for $E \leq 20$ eV. Furthermore, a change of slope occurs for the atmospheric ν_τ flux at $E \approx 20$ GeV. Beyond this energy, the slope of the atmospheric ν_τ flux is identical to that of the galactic-plane ν_τ flux. *For* $E > 20$ GeV*the atmospheric ν_τ flux is intrinsic*, i.e., coming from the D_s decays, whereas the galactic-plane ν_τ flux arises from the oscillation of the ν_μ, which is produced mainly by the π decays. In both cases, the hadrons decay before interacting with the medium. Such a feature dictates the slope of the outgoing neutrino flux. Below 20 GeV, however, the atmospheric ν_τ flux predominantly comes from the ν_μ oscillations, i.e., $\phi^{\mathrm{tot}}_{\nu_\tau}(E) \approx \phi_{\nu_\mu}(E) \cdot \sin^2 2\theta \cdot \sin^2(L/L_{\mathrm{osc}})$ following Eq. (2). Since $L_{\mathrm{osc}} \equiv 4E/\delta m^2 \approx 330$ km for $E = 1$ GeV with $\delta m^2 = 2.4 \cdot 10^{-3}\ \mathrm{eV}^2$, we approximate $\sin^2(L/L_{\mathrm{osc}})$ with $(L/L_{\mathrm{osc}})^2$ so that $\phi^{\mathrm{tot}}_{\nu_\tau}(E) \sim \phi_{\nu_\mu}(E) E^{-2}$. Because the neutrino oscillation effect steepens the ϕ_{ν_τ} spectrum for $E \leq 20$ GeV, the slope change of ϕ_{ν_τ} at $E \approx 20$ GeV is significant.

We have also worked out the comparison of the galactic-plane and the atmospheric ν_τ fluxes for several other zenith angles. For instance, the crossing of the galactic-plane and the atmospheric ν_τ fluxes occurs at $E = 6.0$ GeV for the zenith angle $\xi = 60°$ for $\delta m^2 = 2.4 \cdot 10^{-3}\ \mathrm{eV}^2$ with the maximal mixing. Essentially, the atmospheric ν_τ flux increases with the zenith angle ξ while the galactic-plane ν_τ flux stays unchanged. Moreover, from the phenomenological point of view, a larger ξ only implies a larger atmospheric tau neutrino background while our focus is on the prospective observation of the astrophysical tau neutrinos.

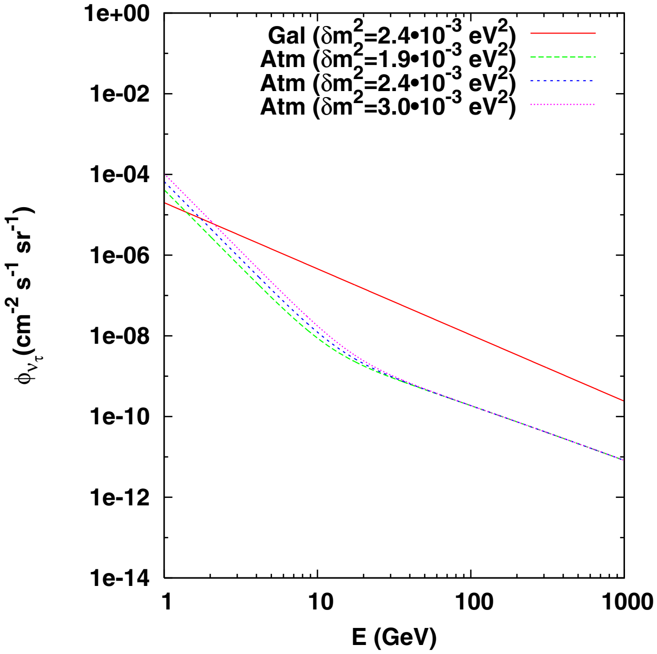

FIG. 4 (color online). The comparison of the galactic-plane and the downward going atmospheric ν_τ fluxes in the presence of neutrino oscillations with maximal mixing as a function of the neutrino energy in GeV. For $\delta m^2 = 2.4 \cdot 10^{-3}\ \mathrm{eV}^2$, both fluxes cross at $E = 2.3$ GeV.

Two key factors determine the angular behavior of the former flux. First, the atmosphere depth is larger for $\xi = 60°$ compared to the downward direction. Second, the atmospheric muon neutrinos are produced more far away from the ground detector in this angle, implying a larger $\nu_\mu \to \nu_\tau$ oscillation probability. We have found that, for $E = 10$ GeV, the downward going muon neutrinos are produced on average about 13 km from the ground detector. At $\xi = 60°$, the above distance increases to 34 km. In the angular range $\xi < 70°$, the curvature of the Earth can be neglected and the angular dependence of the neutrino flux can be easily calculated [19].

In Fig. 5, we show the comparison for the zenith angle $\xi = 180°$ (vertically upward going direction). For $\delta m^2 = 2.4 \cdot 10^{-3}\ \mathrm{eV}^2$ with the maximal mixing the crossing between the two fluxes cross at 800 GeV. The oscillatory behavior in the total atmospheric tau neutrino flux is a manifestation of the narrow zenith angle dependence.

We have so far neglected the 3-body muon-decay contribution to the atmospheric ν_μ flux. As mentioned earlier, this contribution is relevant only for $1\ \mathrm{GeV} \leq E \leq 10$ GeV. The ratio of this contribution to the total atmospheric ν_μ flux is available in the literature [16,19]. For $\cos\xi = 0.4(\xi = 66°)$, $E = 1$ GeV, the ratio is about 50%. It drops to 30% at $E = 10$ GeV for the same ξ [16]. This ratio is not very sensitive to the zenith angle ξ. The error

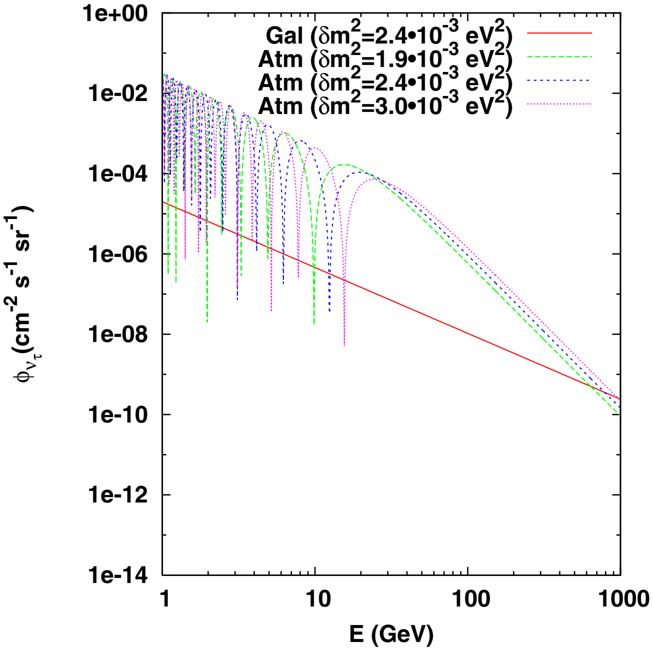

FIG. 5 (color online). The comparison of the galactic-plane ν_τ flux and the atmospheric ν_τ flux coming in the zenith angle $\xi = 180°$ in the presence of neutrino oscillations with maximal mixing as a function of the neutrino energy in GeV. For $\delta m^2 = 2.4 \cdot 10^{-3}$ eV^2, both fluxes cross at $E = 800$ GeV.

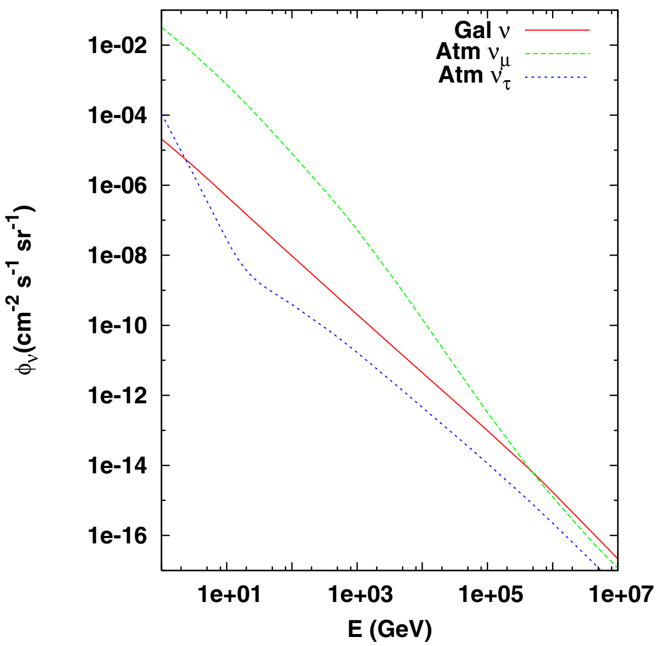

FIG. 6 (color online). An illustrative comparison of the downward going atmospheric ν_μ and ν_τ fluxes and the corresponding galactic-plane neutrino fluxes in the presence of neutrino oscillations as a function of the neutrino energy in GeV. The best-fit values of the neutrino mixing parameters, namely, $\delta m^2 = 2.4 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$, are used. The galactic-plane and the atmospheric ν_μ fluxes cross at $E = 5 \cdot 10^5$ GeV.

due to neglecting this contribution propagates to the determination of the atmospheric ν_τ flux by the neutrino oscillation effect. Numerically, this error is comparable to the uncertainty of the ν_τ flux due to the uncertainty of the δm^2, as $\phi^{\rm tot}_{\nu_\tau}(E) \approx \phi_{\nu_\mu}(E) \cdot \sin^2 2\theta \cdot (\delta m^2 \cdot L/4E)^2$.

V. CONCLUSIONS

The results presented in Figs. 4–6 indicate the opportunities for the tau neutrino astronomy in the GeV energies for the incident zenith angles $0° \leq \xi \leq 180°$ in the two neutrino flavor mixing approximation. The galactic-plane tau neutrino flux *dominates* over the atmospheric tau neutrino background until a few GeV's. Furthermore, for $E \leq 20$ GeV, the former flux has a rather different slope from that of the latter. This is an important criterion for distinguishing the two fluxes, particularly given that the normalization of the galactic-plane tau neutrino flux is still uncertain.

We have pointed out that the dominance of the galactic-plane tau neutrino flux over its atmospheric background in GeV energies is *unique* among all the considered neutrino flavors. This is depicted in Fig. 6. Because of the $\nu_\mu \to \nu_\tau$ neutrino oscillations, the *total* galactic ν_τ flux is identical to that of the galactic ν_μ flux. However, the atmospheric ν_μ flux is much larger than the atmospheric ν_τ flux. As a result, in the *presence* of neutrino oscillations, the crossing energy value for the galactic-plane and the atmospheric ν_μ fluxes is pushed up to $5 \cdot 10^5$ GeV, which is drastically different from the tau neutrino case.

We have estimated the galactic-plane tau neutrino induced shower event rate N_{ν_τ} for the forthcoming one Mega ton class of detectors. It is obtained by convolving the total galactic-plane tau neutrino flux shown in Fig. 6 with the charged-current $\nu_\tau N$ interaction cross section (using the CTEQ6 parton distribution functions [20]). It is found that the N_{ν_τ} can be 4.5 (7.5) for $E > 10$ GeV with a data taking period of 3 (5) years.

A remark concerning the possible background induced by the electron neutrino events and the neutral current events to the prospective observation of tau neutrino events is in order. Below 10^3 GeV, the tau-lepton decay length is less than a mm. This tau lepton is produced in the detector in the galactic-plane tau neutrino induced interactions. There are certain specific signatures of the tau neutrino induced tau leptons such as the appearance of the kink at the tau-lepton decay (absent for the electrons) [21], as well as the relative characteristic fractional energy sharing from the incident neutrino [22]. A large scale finely grained detector with a resolution of a few μm will thus be required to disentangle the galactic-plane tau neutrino induced events from the events induced by the electron neutrinos and the neutral current events on the event-by-event basis.

ACKNOWLEDGMENTS

H. A. thanks Physics Division of NCTS for support. F. F. L and G. L. L. are supported by the National Science Council of Taiwan under the grant number NSC92-2112-M-009-038.

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