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DETECTING EARTH-SKIMMING AND MOUNTAIN-PENETRATING TAU NEUTRINOS*

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In this talk, we discuss issues relevant to the detections of Earth-skimming/mountain-penetrating tau neutrinos. We first argue that there are non-negligible astrophysical tau neutrino fluxes due to neutrino flavor oscillations. We then discuss the rationale for detecting Earth-skimming and mountain-penetrating tau neutrinos. The $\nu_\tau \to \tau$ conversion efficiencies and the tau-lepton event rate are presented.

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1. Introduction

The detection of ultrahigh energy neutrinos is crucial for identifying the extreme energy sources in the universe. There are two distinct strategies for detecting such neutrinos. The first strategy involves the installation of detectors in a large volume of ice or water where most of the scatterings between the candidate neutrinos and nucleons occur [1, 2]. The second strategy detects the air showers caused by the charged leptons produced by the neutrino-nucleon scatterings taking place inside the Earth or in the air, which is far away from the instrumented volume of the detector.

The second strategy is proposed only recently [3]. The Pierre Auger observatory group has simulated the anticipated detection of the air-showers from the decays of τ leptons [4]. The tau air-shower event rates resulting from the Earth-skimming tau neutrinos for different high energy neutrino telescopes are given in [5], where the inelasticity of neutrino-nucleon scatterings and the tau-lepton energy loss are treated approximately. A Monte-Carlo study of tau air-shower event rate was reported not long ago [6].

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However, in that work, only the sum of tau air-shower event rates arising from different directions is given. Hence some of the events may be due to tau-leptons/neutrinos traversing a large distance inside the Earth.

In this talk, I review the calculations [7, 8] on the tau-lepton event rate resulting from high energy Earth-skimming tau neutrinos. The advantage of simultaneous observations of mountain-penetrating [9, 10] and Earth-skimming tau neutrinos will be illustrated with a simple example.

2. The fluxes of astrophysical tau neutrinos and the strategy to detect them

It is well known that the relative flavor ratio for astrophysical neutrinos at the source is approximately $\phi^0_{\nu_e} : \phi^0_{\nu_\mu} : \phi^0_{\nu_\tau} = 1 : 2 : 0$. Although ν_τ flux is rather suppressed at the source, it is not negligible at the detector due to the neutrino flavor oscillations. With a vanishing θ_{13} and $\sin^2 2\theta_{\rm atm} = 1$ in the neutrino mixing matrix, one arrives at [11] $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$.

As tau neutrinos skims the Earth, the detectable tau leptons are those produced near the surface of the Earth, approximately within a tau-lepton range. In this regard, it is meaningful to define the following effective tau-lepton production probability:

$$P_\tau = \frac{R_\tau(E_\tau)}{l^{cc}_{\nu_\tau}(E_{\nu_\tau})}, \tag{1}$$

where $R_\tau(E_\tau)$ is the tau-lepton range as a function of tau-lepton energy, while $l^{cc}_{\nu_\tau}(E_{\nu_\tau})$ is the tau neutrino charged-current interaction length inside the Earth as a function of the tau-neutrino energy. For the moment, let us take $E_\tau = E_{\nu_\tau} \equiv E$. The behavior for $R_\tau(E)$ is well known [7, 12]. It increases slowly with energy for $E_\tau > 10^8$ GeV. In the standard rock where $\rho = 2.65$ g/cm^3, R_τ approaches to 20 km as E approaches to 10^{12} GeV. As shown in Ref. [7], R_τ begins to level off for $E > 10^{12}$ GeV. Hence the medium with a depth about 20 km is most favorable for producing the tau-lepton flux. Beyond this depth, the incoming tau-neutrino flux is attenuated before producing the tau leptons. Due to this property, the Earth-skimming experiment can in fact be implemented using the mountain as a target [9,10]. The interaction length $l^{cc}_{\nu_\tau}(E)$ scales as $E^{-0.363}$ [13]. Hence $l^{cc}_{\nu_\tau}(E)$ decreases as E increases. From the behaviors of $R_\tau(E)$ and $l^{cc}_{\nu_\tau}(E)$, we easily see that the effective tau-lepton production probability, $P_\tau(E)$, increases with E. Therefore the `Earth-skimming` detection strategy favors the higher energy tau neutrinos. In the standard rock, $P_\tau(E)$ rises from 10^{-4} to more than 10% as E increases from 10^7 GeV to 10^{11} GeV.

3. The conversion efficiency for $\nu_\tau \to \tau$

The determination of $\nu_\tau \to \tau$ conversion inside the Earth involves calculating the neutral and charged current neutrino–nucleon scattering cross section [13]. It also requires the calculation of tau-lepton energy loss and decays after its production. The processes contributing to the tau-lepton energy loss in the medium includes ionization [14], bremsstrahlung [15], the e^+e^- pair production [16] and the photo-nuclear processes [12,17]. Applying CTEQ6 parton distribution function [18] for neutrino–nucleon scattering and taking into account the above tau-lepton energy loss mechanisms, one obtains [8] the tau-lepton spectra depicted in Figs. 1, and 2. For the medium length, $L = 20$ km, inside the standard rock, the $\nu_\tau \to \tau$ conversion efficiencies are 1.5%, 4.8%, and 10.9% for initial $E_\nu = 10^9$, 10^{10} and 10^{11} GeV's, respectively. For $L = 100$ km, the conversion efficiencies become 1.3%, 3.4% and 5.3%, respectively. The conversion efficiency decreases considerably for $E_\nu = 10^{11}$ GeV due to the attenuation effect mentioned before.

It is important to see how an anomalous neutrino–nucleon scattering cross section may affect the final tau-lepton flux. In stead of following specific models for anomalous neutrino–nucleon cross section [19, 20], let us simply investigate the case with $\sigma_{\rm NEW} = 10\,\sigma_{\rm SM}$, *i.e.*, the neutrino–nucleon

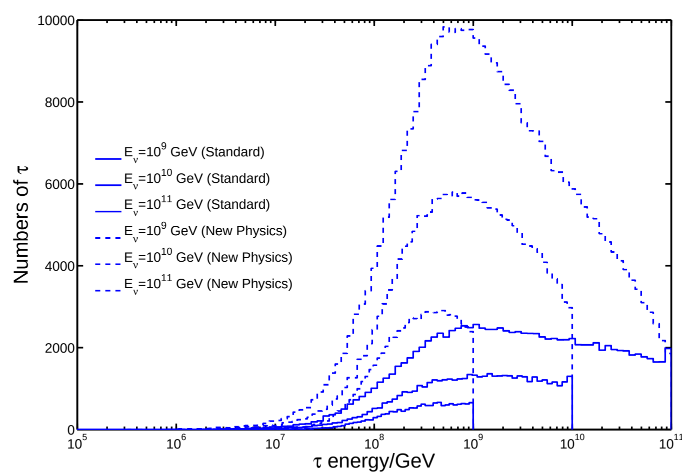

Fig. 1. The tau-lepton energy spectra resulting from Earth-skimming tau neutrinos with different initial energies and a 20 km medium length. The solid lines are results obtained from standard neutrino–nucleon scattering cross section while the dashed lines are those obtained from enhanced scattering cross section, $\sigma_{\rm NEW} = 10\,\sigma_{\rm SM}$. Each curve is generated with 10^6 incoming neutrino events.

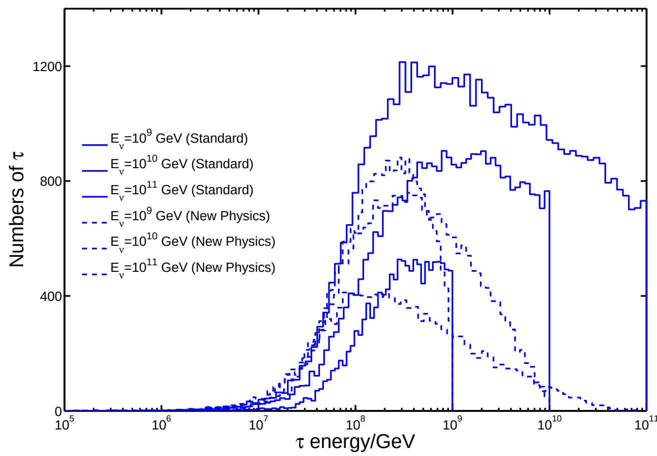

Fig. 2. The same as Fig. 1 except that the medium length is 100 km.

cross section is enhanced by 10 times[1]. For $L = 20$ km, the new-physics induced tau-lepton spectra dominate the standard-model spectra as shown in Fig. 1. The $\nu_\tau \to \tau$ conversion efficiencies become 7.3%, 20.1%, and 34.9% for initial $E_\nu = 10^9$, 10^{10} and 10^{11} GeV's, respectively. On the other hand, for $L = 100$ km, Fig. 2 shows that the enhanced neutrino–nucleon cross section attenuates the incoming neutrino beam such that the above conversion efficiencies turn into 2.4%, 2.5% and 1.3%, respectively. Clearly, except for $E_\nu = 10^9$ GeV, these efficiencies are lower than the standard-model case. We have seen that the enhanced neutrino–nucleon cross section could either increase or decrease the tau-lepton flux depending on the medium depth. Hence an experiment that can simultaneously detect mountain-penetrating and Earth-skimming tau neutrinos [9,10], with the medium lengths few tens of kilometers and few hundreds of kilometers, respectively, could be sensitive to the enhancement of neutrino–nucleon cross section.

4. Tau-lepton event rate

We have calculated the tau-lepton flux resulting from Earth-skimming cosmogenic tau neutrinos [7]. The flux of cosmogenic tau neutrinos is inferred from [21] by neutrino flavor oscillations [11]. The tau-lepton flux is found to be insensitive to the medium depth for 10 km $\leq L \leq$ 100 km. It peaks at energies between 10^8 and 10^9 GeV. The integrated tau-lepton flux in this energy range is $\Phi = 8.2 \times 10^{-2}\text{km}^{-2}\text{yr}^{-1}\text{sr}^{-1}$. Therefore, to detect one event per year in this energy interval, the acceptance of a fluorescence detector must be larger than 120 km^2 sr assuming a 10% duty cycle.

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REFERENCES

[1] See F. Halzen, *Acta Phys. Pol. B* **36**, 481 (2005), these proceedings and references therein.

[2] See T. Montaruli, *Acta Phys. Pol. B* **36**, 509 (2005), these proceedings and references therein.

[3] G. Domokos, S. Kovesi-Domokos, `hep-ph/9805221`. See also, D. Fargion, *Astrophys. J.* **570**, 909 (2002).

[4] X. Bertou, P. Billoir, O. Deligny, C. Lachaud, A. Letessier-Selvon, *Astropart. Phys.* **17**, 183 (2002).

[5] J.L. Feng, P. Fisher, F. Wilczek, T.M. Yu, *Phys. Rev. Lett.* **88**, 161102 (2002).

[6] S. Bottai, S. Giurgola, *Astropart. Phys.* **18**, 539 (2003).

[7] J.J. Tseng *et al.*, *Phys. Rev.* **D68**, 063003 (2003) [`astro-ph/0305507`].

[8] C.-H. Iong, *Master Thesis*, NCTU (2004).

[9] G.W. Hou, M.A. Huang, Eds. H. Athar, G.-L. Lin, K.-W. Ng, World Scientific, Singapore 2002, p. 105 [`astro-ph/0204145`].

[10] P. Yeh *et al.* [NuTel Collaboration], *Mod. Phys. Lett.* **A19**, 1117 (2004).

[11] H. Athar, M. Jezabek, O. Yasuda, *Phys. Rev.* **D62**, 103007 (2000).

[12] S.I. Dutta, M.H. Reno, I. Sarcevic, D. Seckel, *Phys. Rev.* **D63**, 094020 (2001).

[13] R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, *Phys. Rev.* **D58**, 093009 (1998) [`hep-ph/9807264`].

[14] B. Rossi, *High Energy Particles*, Prentice Hall, Englewood Cliffs, NJ, USA 1952.

[15] A.A. Petrukhin, V.V. Shestakov, *Can. J. Phys.* **46**, S377 (1968).

[16] R.P. Kokoulin, A.A. Petrukhin in *Proceedings of the XII International Conference on Cosmic Rays* Hobart, Tasmania, Australia, 1971, Vol. 6.

[17] L.B. Bezrukov, E.V. Bugaev, *Sov. J. Nucl. Phys.* **33**, 635 (1981) [Yad. Fiz. **33**, 1195 (1981)]. For a recent discussion, see E.V. Bugaev, Y.V. Shlepin, *Phys. Rev.* **D67**, 034027 (2003) [`hep-ph/0203096`].

[18] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky, W.K. Tung, *J. High Energy Phys.* **0207**, 012 (2002) [`hep-ph/0201195`].

[19] J. Alvarez-Muniz, J.L. Feng, F. Halzen, T. Han, D. Hooper, *Phys. Rev.* **D65**, 124015 (2002) [`hep-ph/0202081`].

[20] M.A. Huang, C.H. Iong, G.L. Lin, work in progress.

[21] R. Engel, D. Seckel, T. Stanev, *Phys. Rev.* **D64**, 093010 (2001) [`astro-ph/0101216`].